Simulation Frameworks: Hadron Colliders, Snowmass 2013

Snowmass Energy Frontier Workshop

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Sanjay Padhi

University of California, San Diego

with

A. Avetisyan (Boston), J. Berryhill (FNAL), K. Black (Boston), C. Brock (MSU), R. Cavanaugh (FNAL/UIC),

S. Chekanov (ANL), K. Hatakeyama (Bayler), J. Hirschauer (FNAL), B. Klima (FNAL), A. Kotwal (Duke Uni.),

T. LeCompte (ANL), S. Malik (UNL/FNAL), K. Mishra (FNAL), M. Narain (Brown), J. Olsen (Princeton),

M. Peskin (SLAC), S. Sharma (FNAL), M. Slyz (FNAL), J. Stupak (Purdue), et. al.

Disclaimer:

The current study is based on the best understanding of both ATLAS and CMS detectors. The "string" ATLAS or CMS in this talk refers to the respective detectors but not to the future decisions on the performance by the collaborations. With larger pile-ups there will be severe challenges and the full (upgraded) detector performance/potential will be explored by the collaborations in forthcoming months/years.

Acknowledgments:

We really like to thank both the ATLAS and CMS collaborations for valuable input. Special thanks to members from both groups working hard on common LHC detector configurations and parameters which can be used for the Snowmass studies.

Outline

- Introduction
- Challenges with LHC and detector upgrades
- Overview of current ATLAS and CMS detectors
- Combined LHC detector for Snowmass Studies

  - Parameterized detector simulation using Delphes (with Pileup)
- Performance studies using parameterized simulation
- Common backgrounds for Snowmass – Generation and Simulation
- Storage and replication of samples
- Thoughts on expected increase in pileup interactions
- Summary and Conclusion

Introduction

The LHC has been performing beyond expectations.

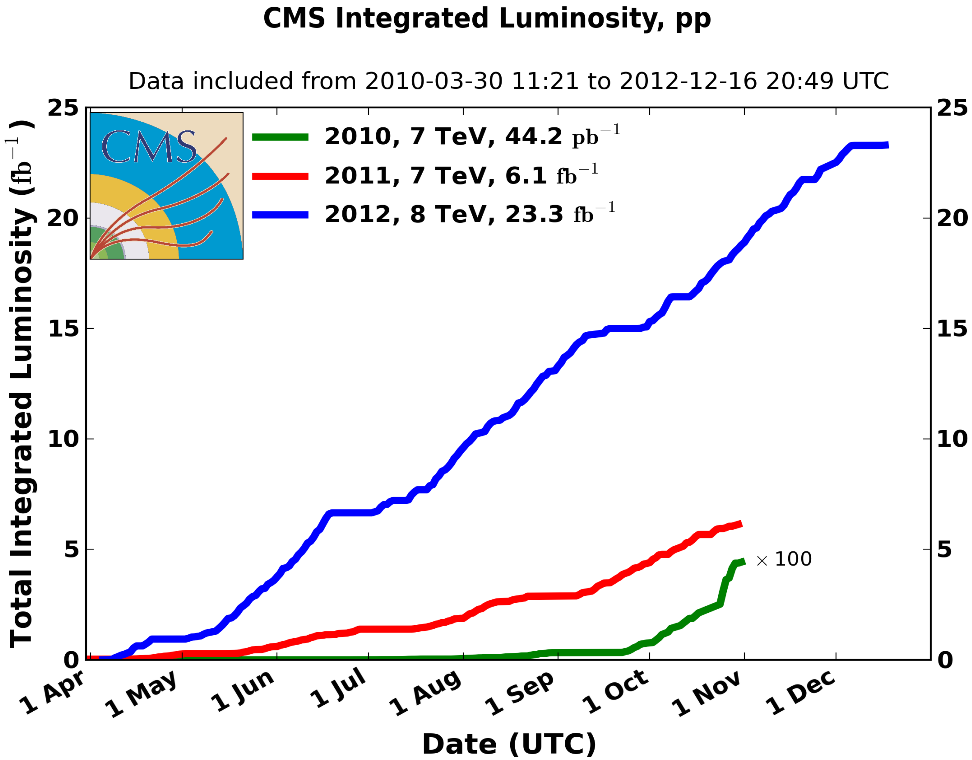
The peak luminosity in 2012 has been 7 x 10^{33} Hz/cm^2 at 50 ns bunch crossing

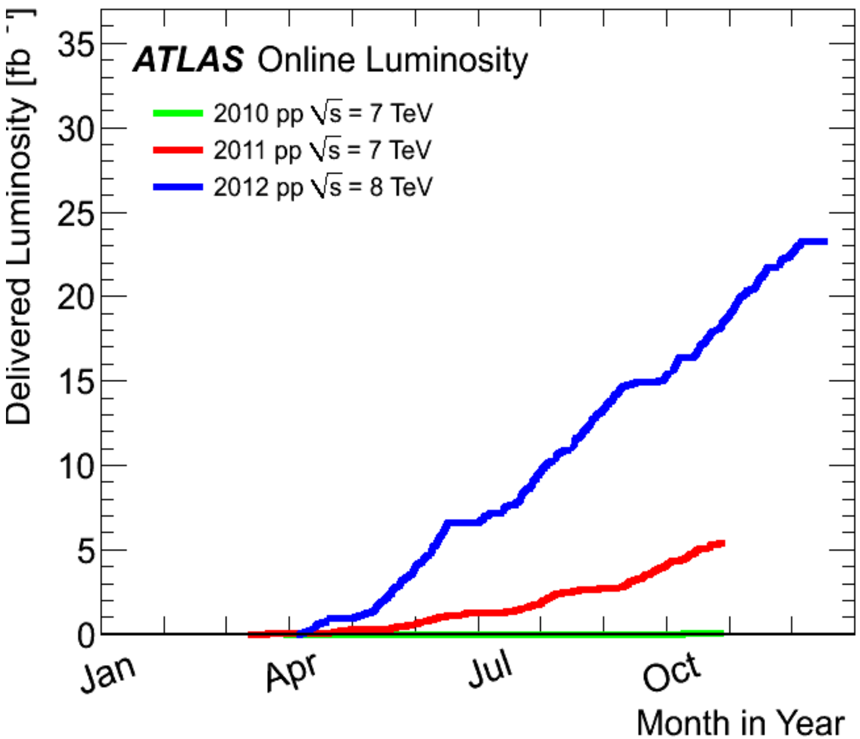
- This corresponds to on average ~25 pileup pp interactions

About ~ 25 fb^{-1} of integrated luminosity has been collected by both experiments

ATLAS and CMS experiments are performing extremely well under these conditions

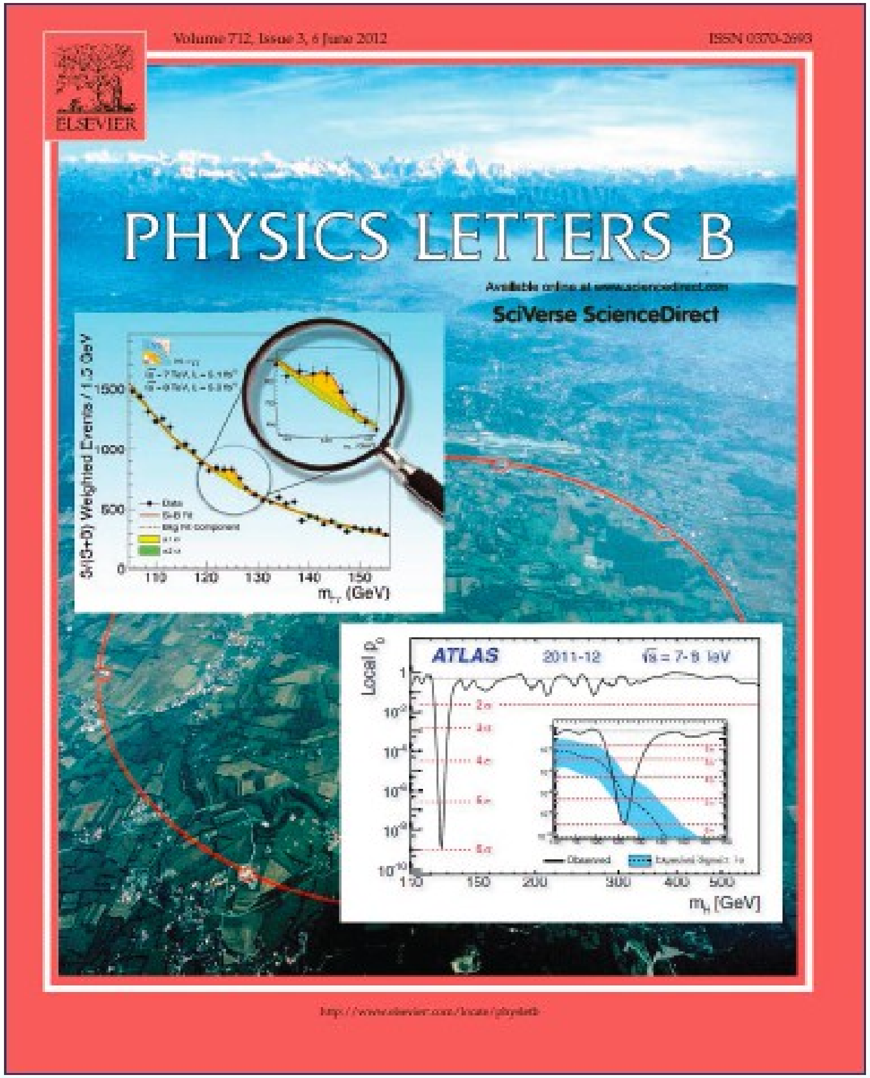
Overall operation efficiency by the detectors = 95% - 99%





The highlight of a remarkable year 2012

Rolf Heuer, CERN-DG, 2013



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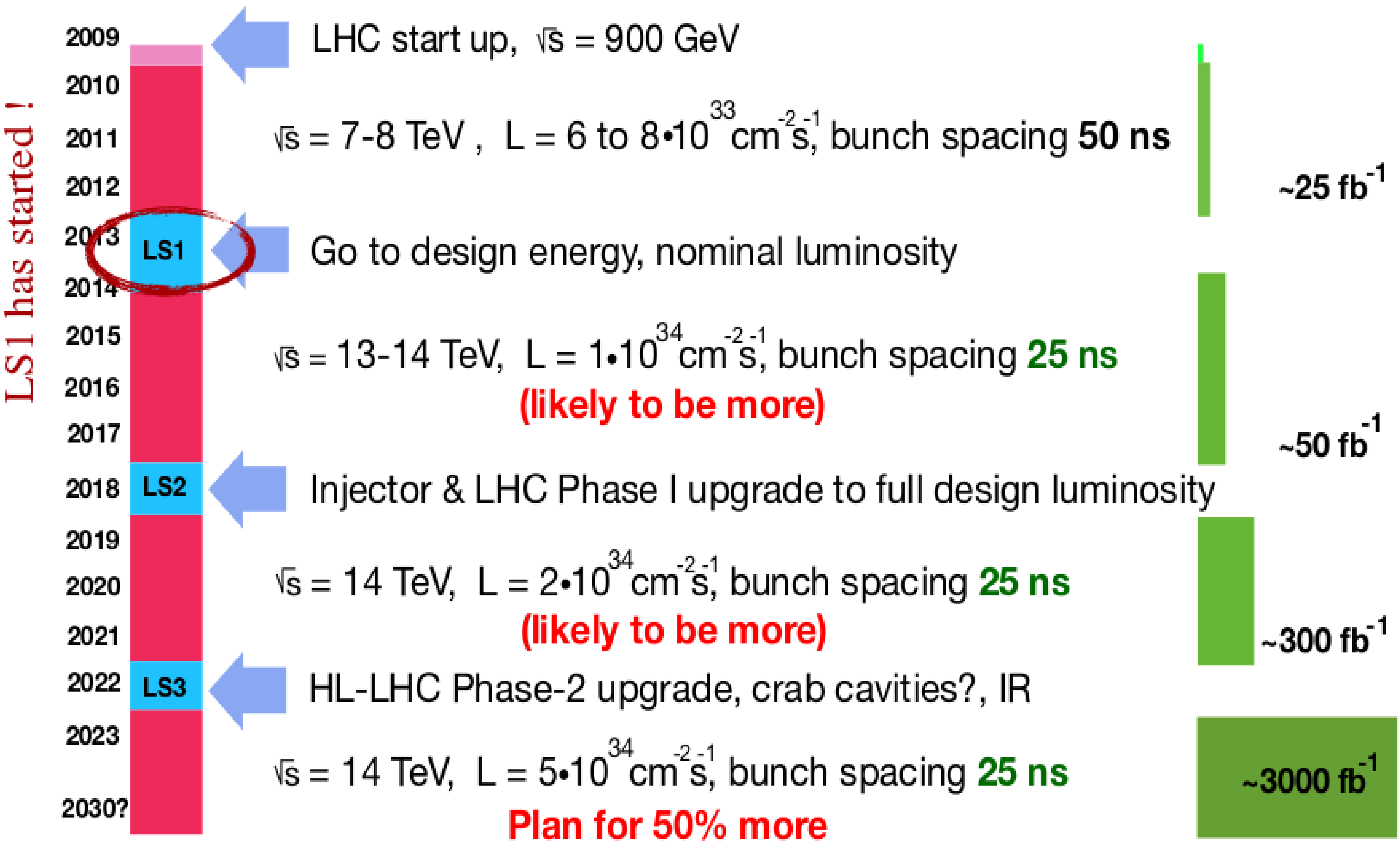
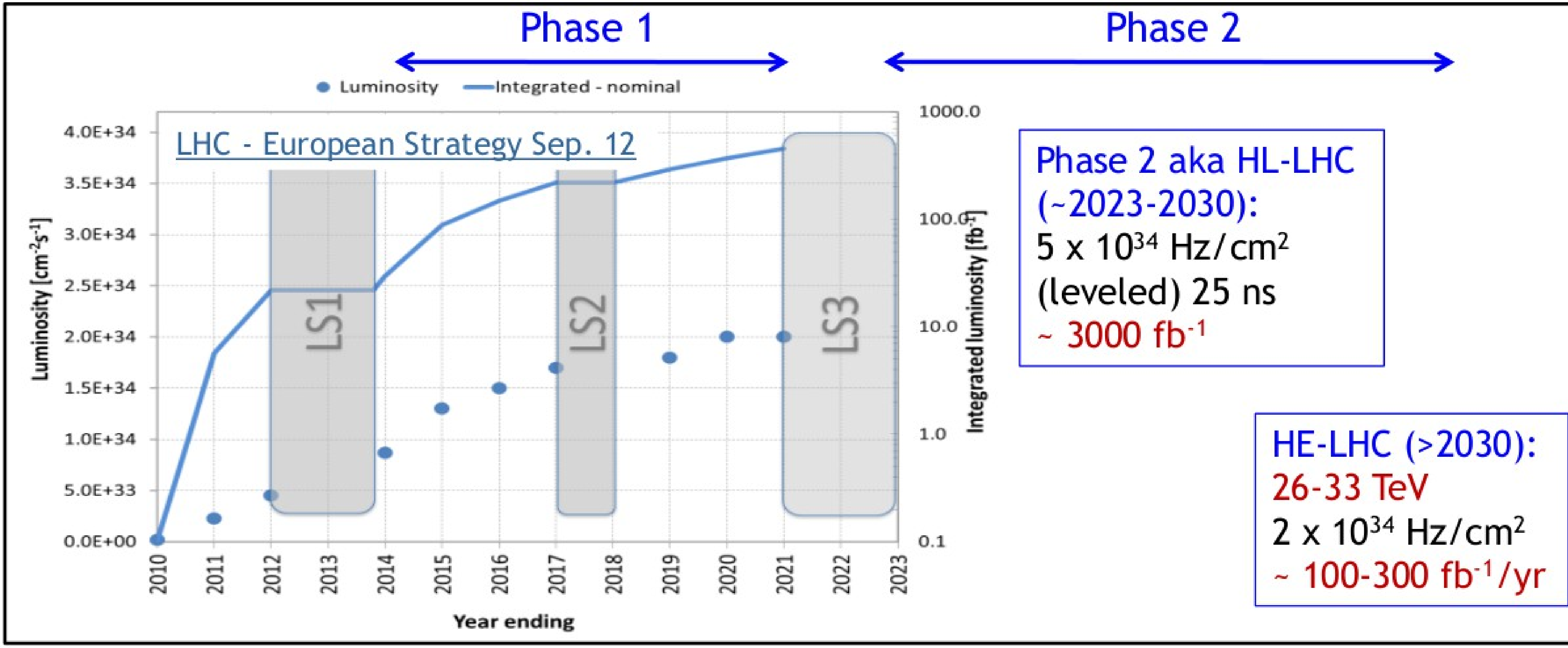
But, this is just the beginning of a long journey!

LHC Evolution



LHC Evolution



LHC Phase-I: 13/14 TeV pp collisions with 50 – 80 pileup events

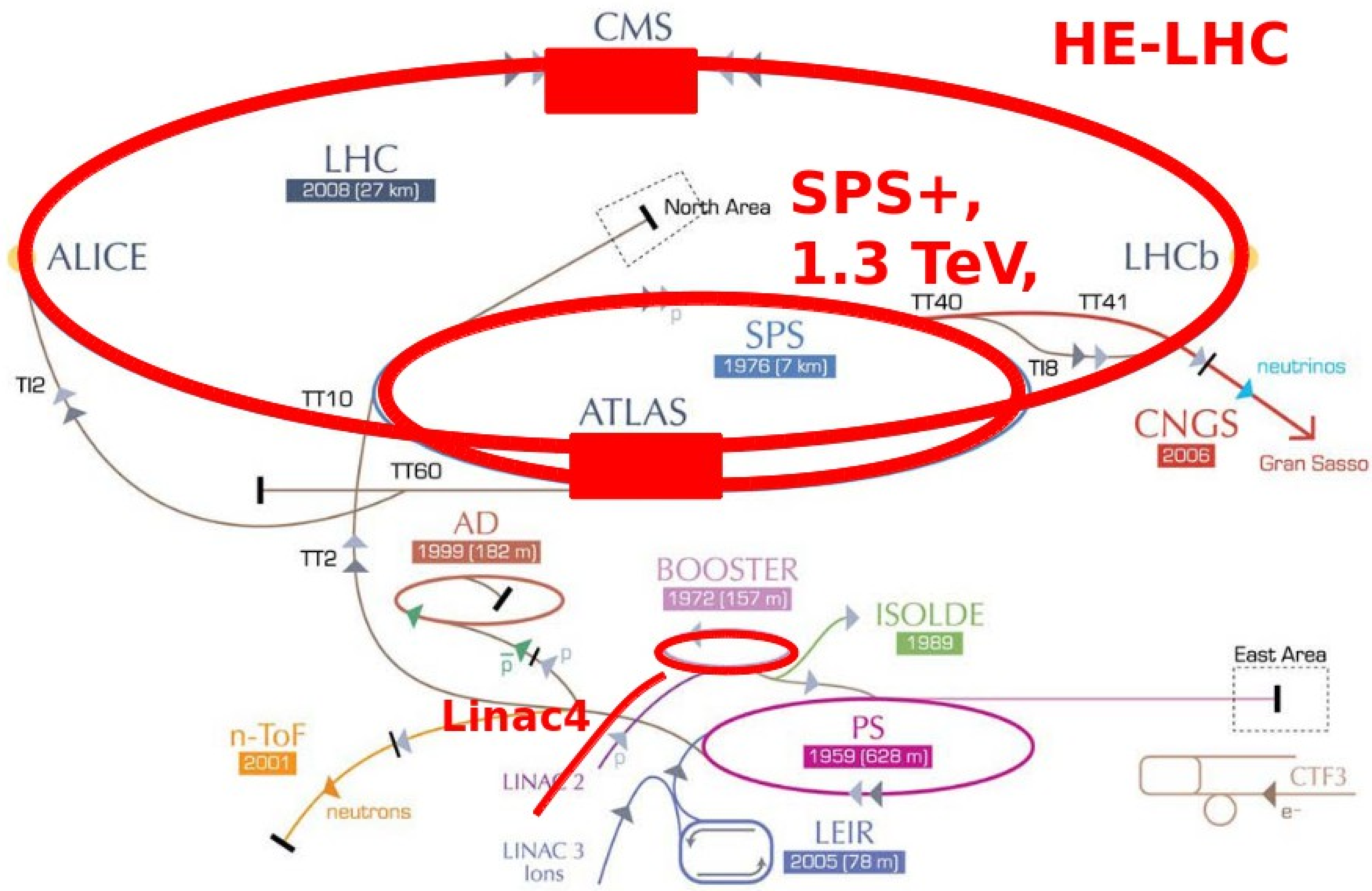
LHC Phase-II (HL-LHC): 13/14 TeV pp collisions with ~140 pileup events

LS1-LS2 baseline: 0.8 → 1.7 x 10^{34} Hz/cm^2 at 25 ns. ~300 fb^{-1} by LS2 @ 13-14 TeV

- Alternative with 1.8 x10^{34} Hz/cm^2 at 50 ns with lumi-leveling.

After LS2 injection chain upgrades: 25 ns will allow ≥ 2 x 10^{34} Hz/cm^2

High Energy LHC (HE–LHC) with 33 TeV pp collisions (CERN-ATS-2010-177)



LHC parameters

LHC: 300 fb-1 / exp. ; HL-LHC: 3000 fb-1 / exp.

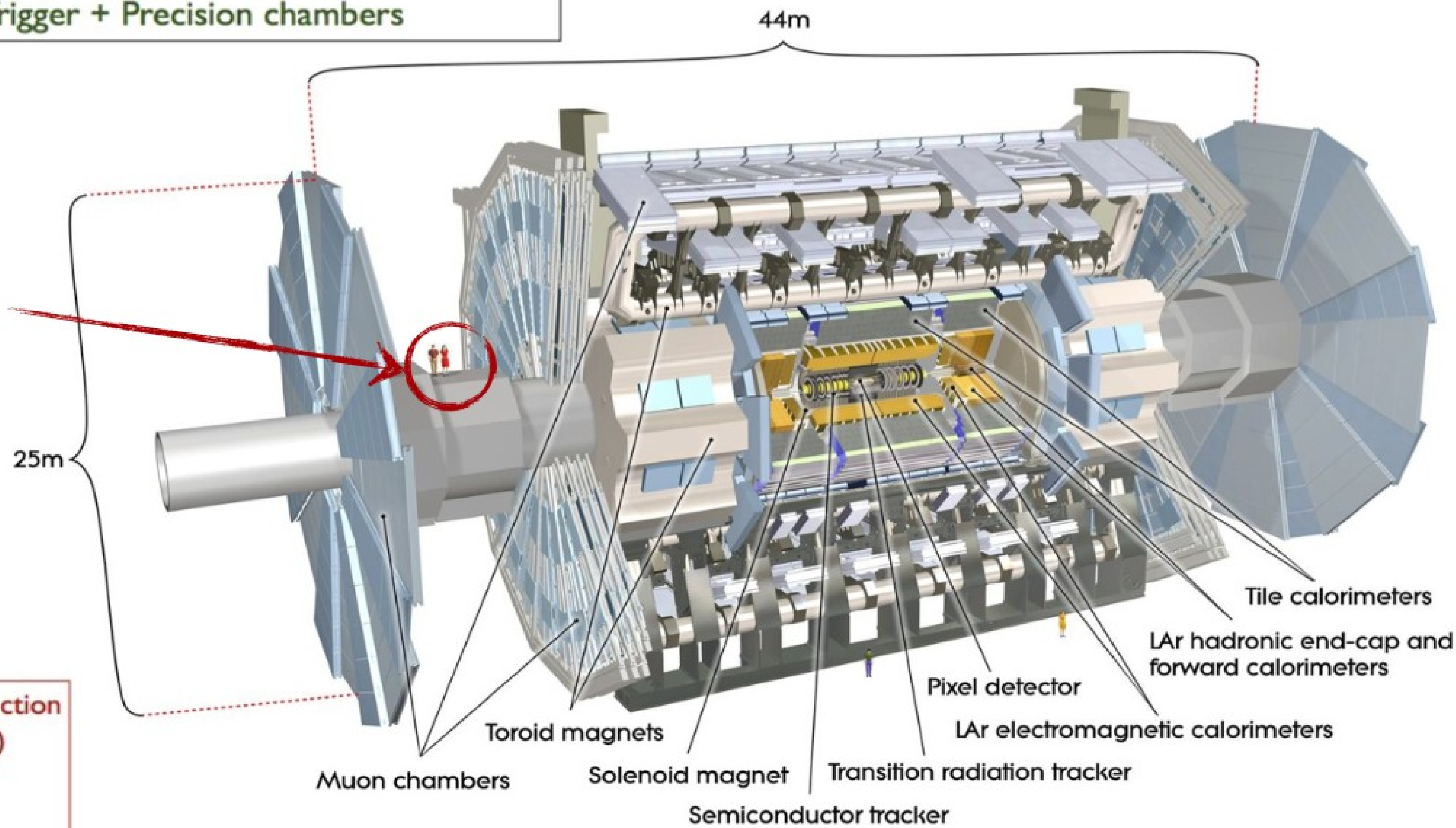
parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
full crossing angle [μrad]	285	590	240	100
stored beam energy [MJ]	362	694	601	5410
SR power per ring [kW]	3.6	6.9	82.5	2356
arc SR heat load dW/ds [W/m]	0.21	0.40	3.5	99
energy loss per turn [keV]	6.7	6.7	201.3	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	1.9	1.6	1.3
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	21.0	77	634
init. horiz. IBS emit. rise time [h]	103	15.4	40	306
peak events per crossing	19	140 (lev.)	190	190
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	7.4	5.0	5.0
beam lifetime due to burn off [h]	45	11.6	6.3	18.6
optimum run time [h]	15.2	8.9	6.5	12.2
opt. av. int. luminosity / day [fb^{-1}]	0.47	3.7	1.5	2.3

O. Dominguez, L. Rossi, F. Zimmermann

Overview of the current ATLAS detector

Multi-purpose, high resolution and hermetic detector

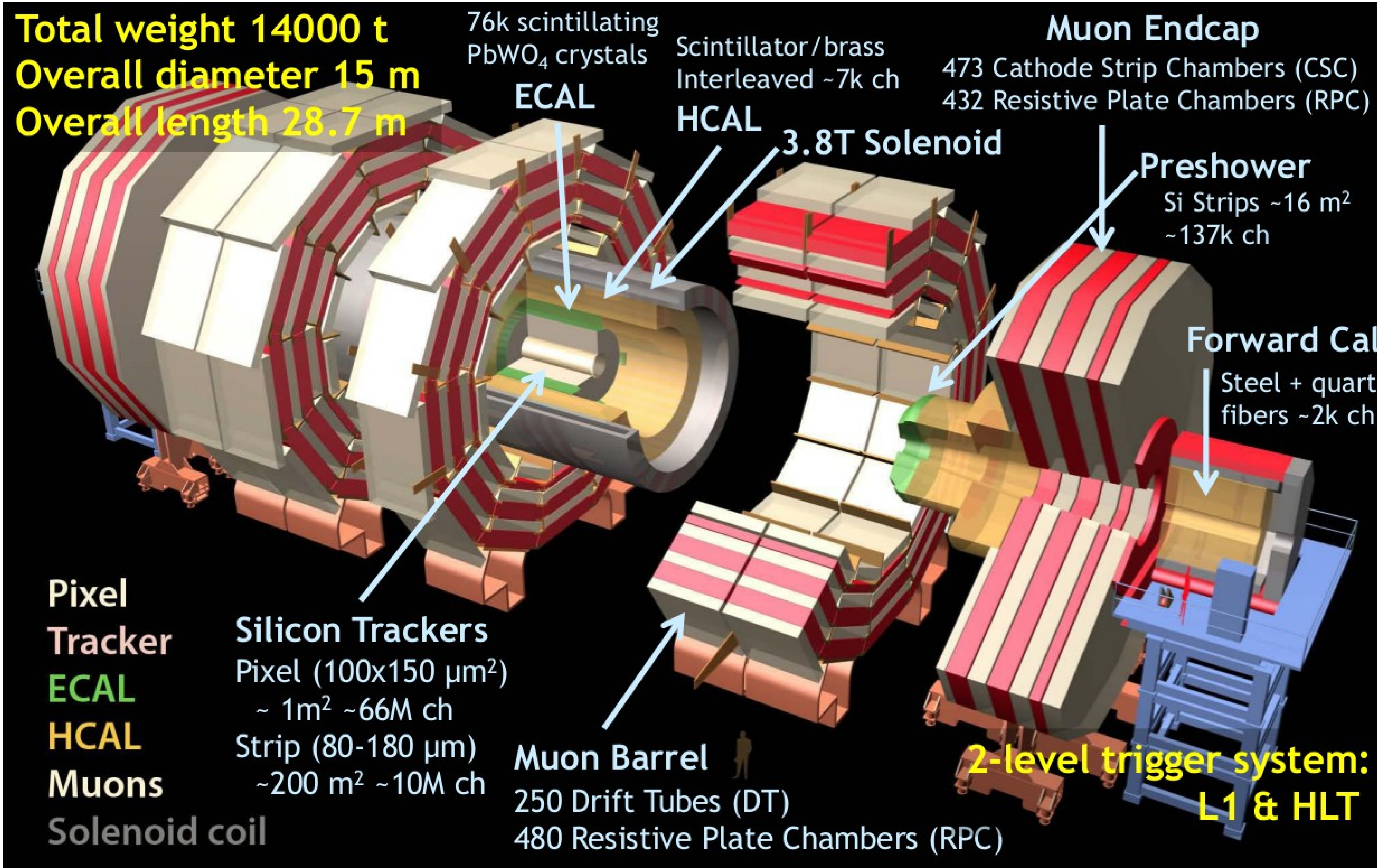
Magnets:	Central Solenoid + 3 Toroids
Tracking:	Silicon, Transition Radiation Tracker
Calorimeter:	EM (LAr), Had Cal
Muon:	Trigger + Precision chambers



Object Reconstruction

- leptons (e, μ, τ)
- photons
- jets
- b-jets
- Etmiss

Overview of the current CMS detector



Upgrade Strategy: ATLAS

LS1 Projects & Upgrades:

- New insert-able pixel layer
- Install staged chambers in the muon spectrometer to complete geometrical coverage
- A lot of consolidation work

Complete original detector
Address operational issues
Start upgrade for high PU

Phase 1 Upgrades:

- New Small Wheel forward muon chambers
- Finer calorimeter readout at Level-1
- Fast Track Trigger (FTK)
- Trigger/DAQ upgrades (including for above)
- Forward Physics Detector

Maintain performance at high PU

Phase 2 Upgrades:

- Tracker replacement
- New Trigger/DAQ L0/L1 configuration
  - New Calorimeter Front End Electronics
  - New Muon Front End Electronics
- Forward Calorimeters (if required)

Maintain performance at extreme PU
Sustain rates and radiation doses

Upgrade Strategy: CMS

LS1 Projects & Upgrades:

- Completes muon coverage (ME4)
- Improve muon trigger (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD → SiPM)
- A lot of consolidation work

Complete original detector
Address operational issues
Start upgrade for high PU

LS1 LS2 LS3

Phase 1 Upgrades:

- New Pixels, HCAL SiPMs and electronics, and L1-Trigger
- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems

Maintain performance at high PU

Phase 2 Upgrades: scope to be defined in Technical Proposal (2014)

- Tracker replacement
- Forward Calorimeters
- Further Trigger/DAQ upgrade: Track Trigger

Maintain performance at extreme PU
Sustain rates and radiation doses

Simulation framework for Snowmass 2013

Simulation framework for Snowmass

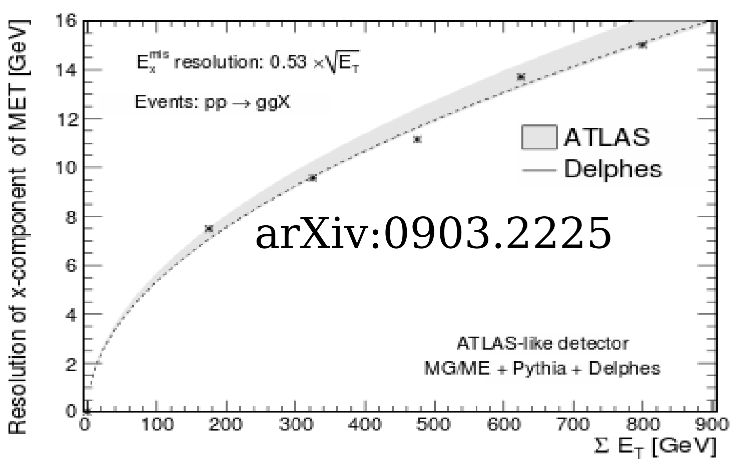
For long range physics planning at Snowmass, we need to make a physics case

- with high luminosity running, higher energy, etc.

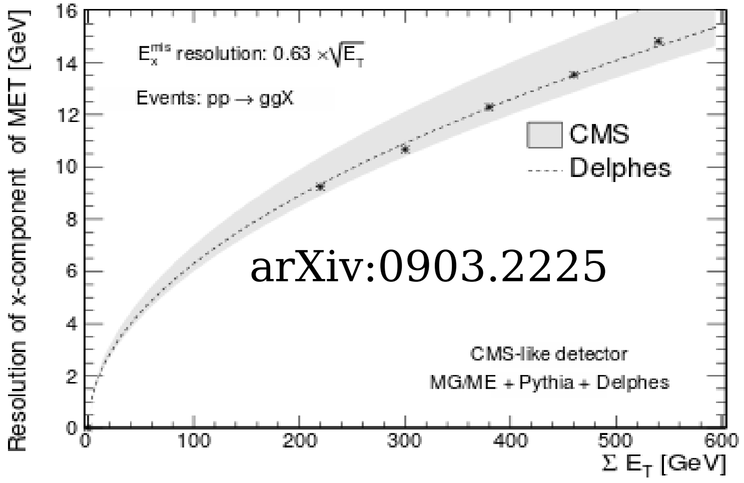
Experiments are currently re-evaluating their full detector simulation framework to accommodate the expected HL performance with large pileup events.

For last EU strategy meeting:

- ATLAS: Simulates the present analyses with parametrized (smeared?) Phase-II detector response with large pileups (See: ATLAS-140 string in next slides)
- CMS : Extrapolates present results assuming Phase-II detector
  - Data at HL-LHC ~ Same as 2012 data
  - The goal was to retain acceptance, resolution, background and fake rates.



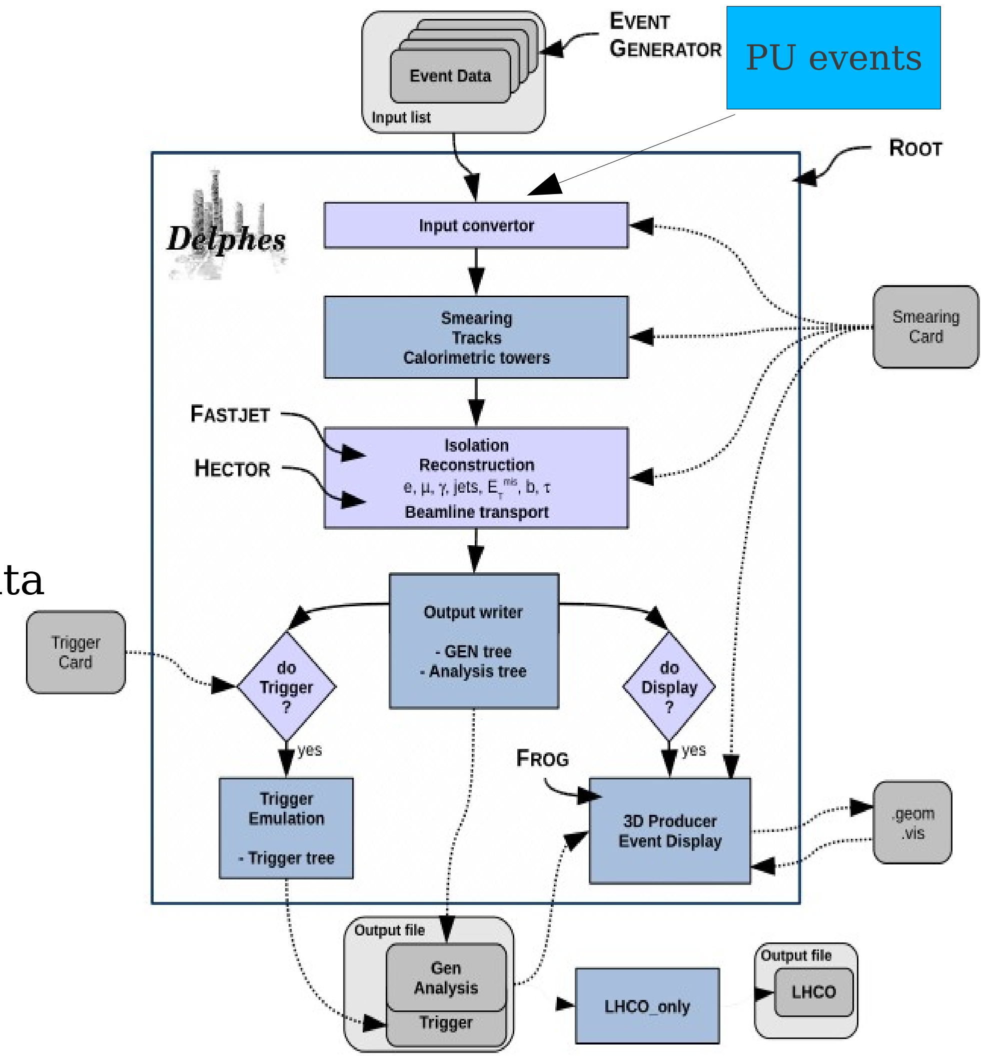
← No PU events →



Simulation framework for Snowmass

Delphes-3 fast simulation (https://cp3.irmp.ucl.ac.be/projects/delphes)

- Delphes3 supports addition of PU events
- Many improvements were motivated based on current studies



For Phase-I studies:

We plan to use Delphes3 framework with:

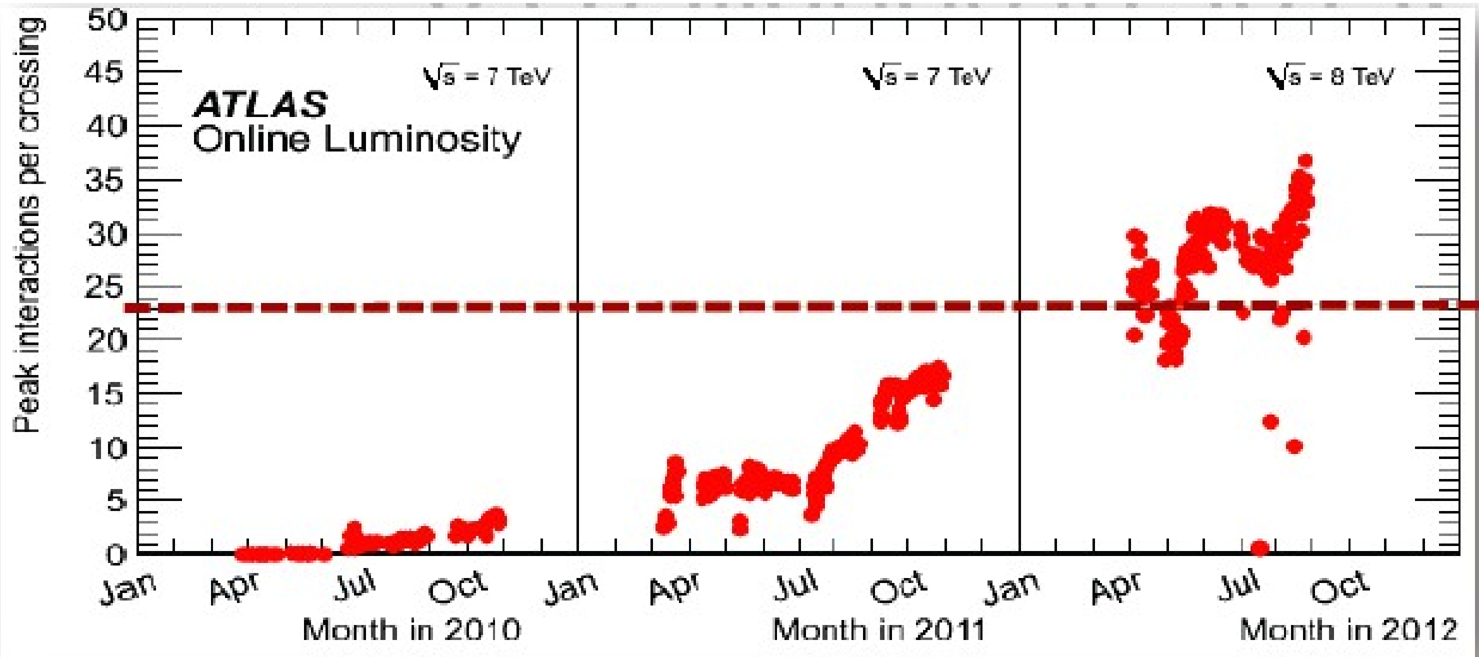
- realistic detector performance with PU =50
- parameterize using available full simulation
- retain object performance as obtained using data
- use best of both ATLAS/CMS performance (if publicly available)

Validation is crucial for all of these to work

For Phase-II studies:

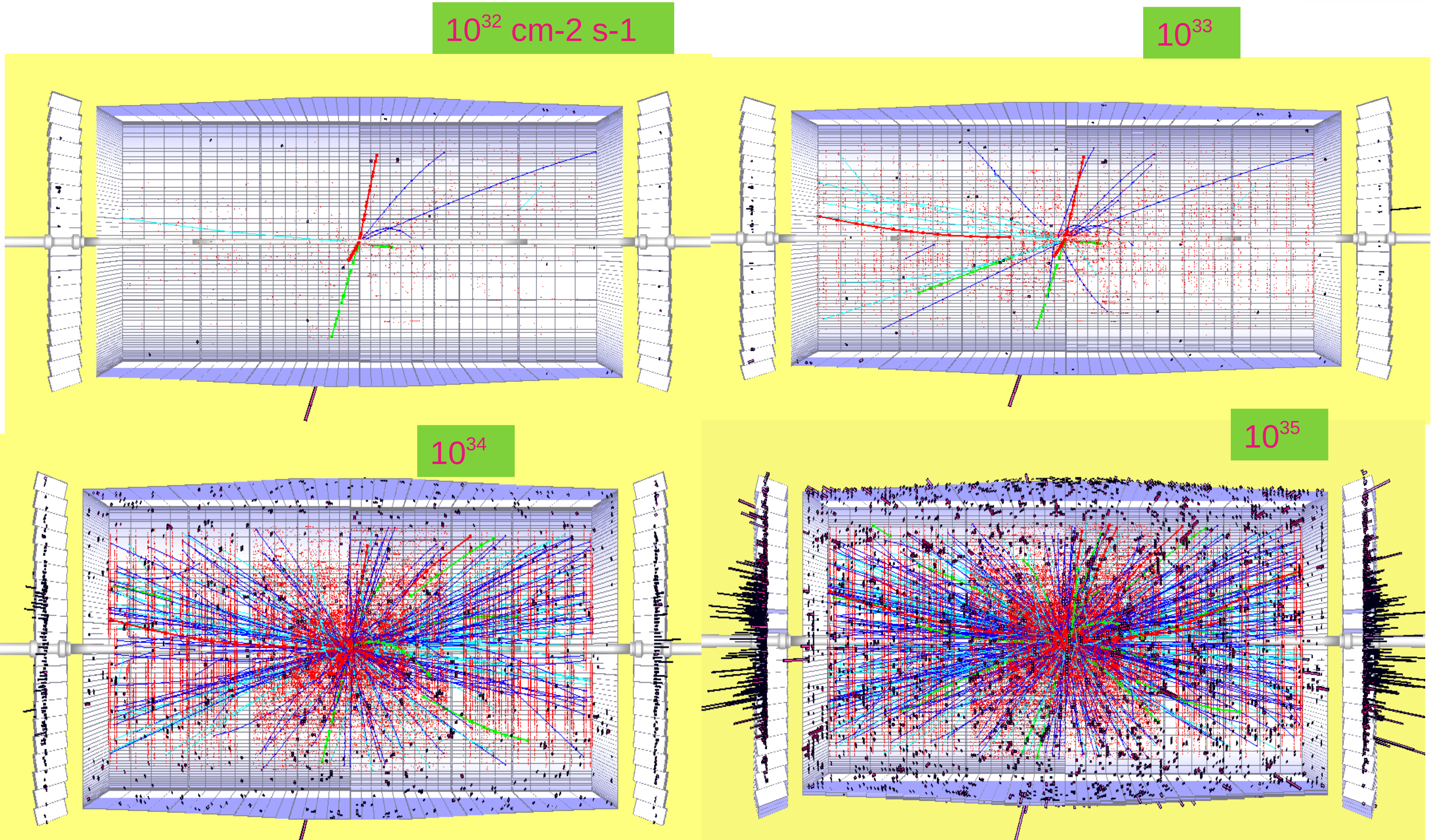
- use higher pileups – 140
- assume the upgraded detector with best available performance
- use best of both ATLAS/CMS expected performance
- **pileup subtraction will be the key**

Challenges with Pileups - 2012



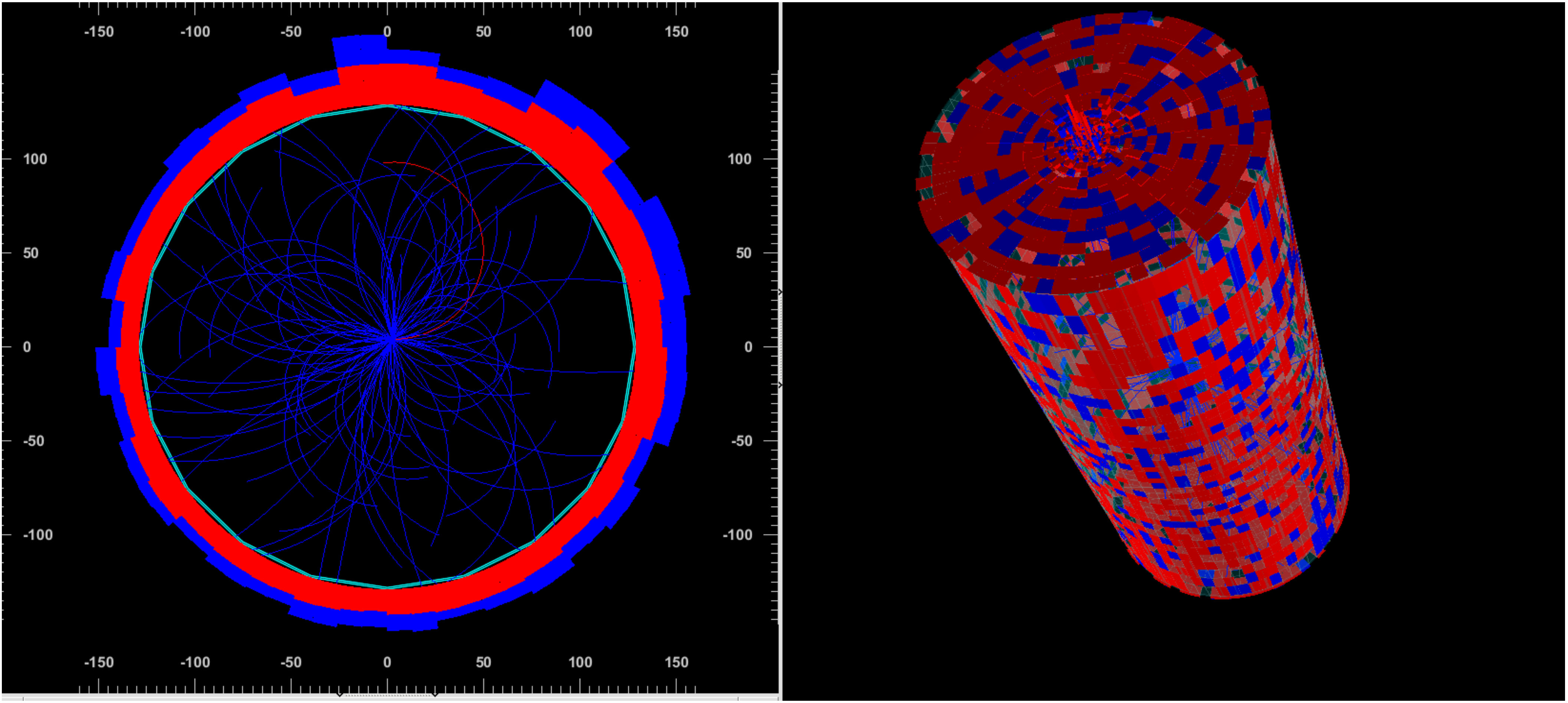
~Design value
(L=10^{34}, 25ns)

Challenges with Pileups for objects



HL-LHC provides challenges for Trigger, Tracking and Calorimetry – for low/medium Pt objects

Event display: 140 PU (Delphes - 3)

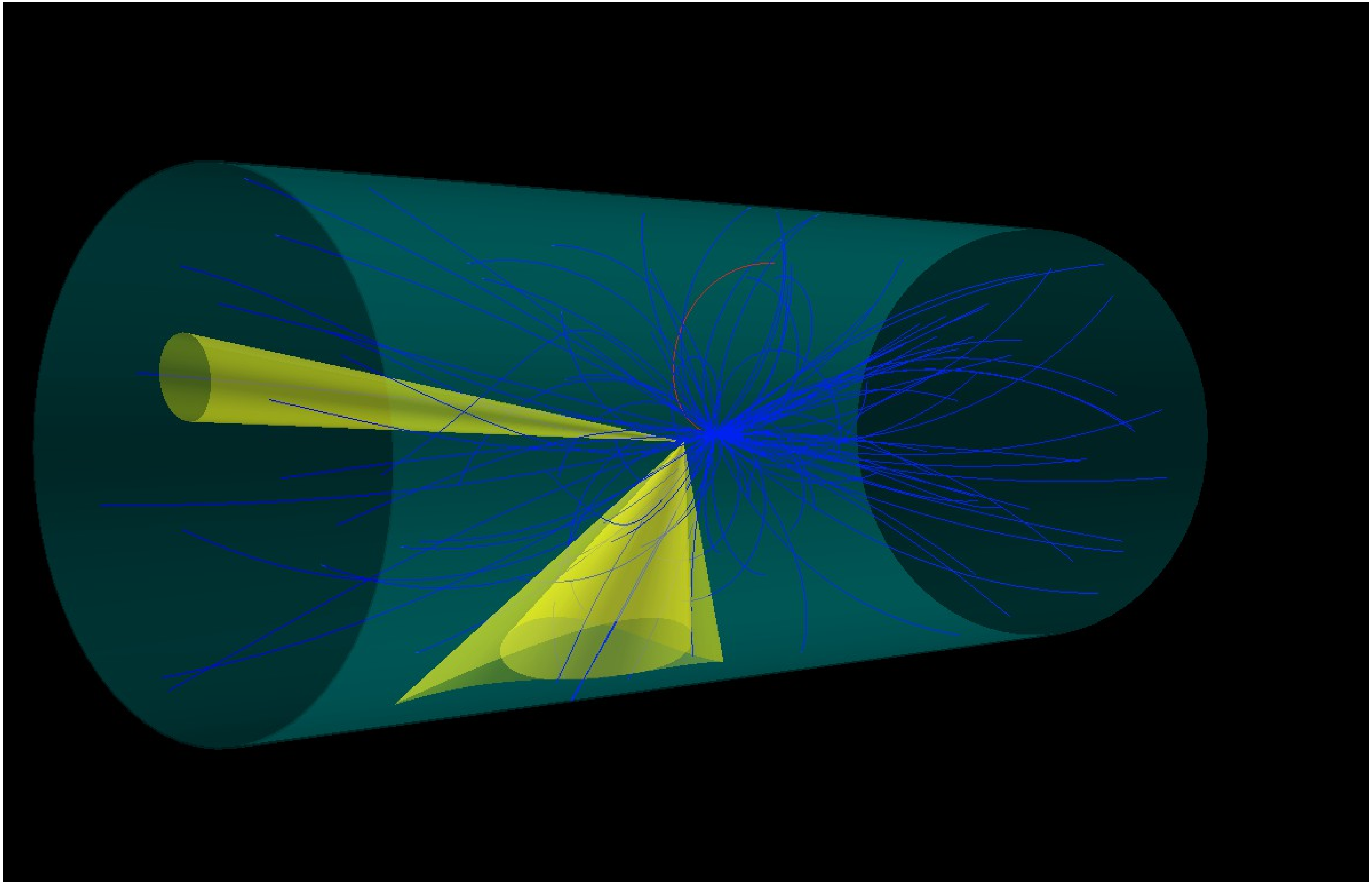


W → e ν (Pythia):

- Added with 140 PU from Minbias events (CMS Z2* tune)

- **Jets can originate from pileup events (Not possible with Jet smearing alone)**

Event display with Delphes-3



Object Performance Studies

Performance studies

The performance studies are based on general understanding of current detectors

Pile-ups (PUs) are extracted using Minbias events with Z2* tune (CMS Tune)

Pile-up is based on implementation in Delphes-3.0.4

(with publicly available parameters from the experiments)

- Charged particles are subtracted at the mixing level
- Similar to vetoing “Charged tracks” NOT coming from the primary vertex.
- Neutral particles are subtracted based on fastjet area method (ρ method)
- In the endcap/fcal (outside the tracker acceptance) ρ method is used

The Z vertex spread in the beam direction, assuming gaussian - 5 cm

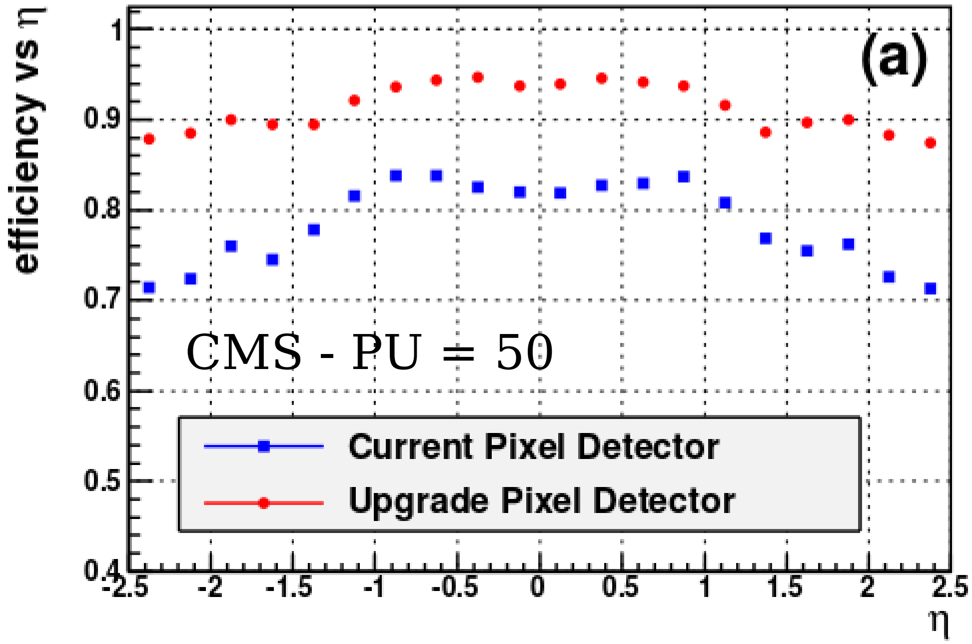
The resolution spread in the Z vertex direction – 0.1 cm

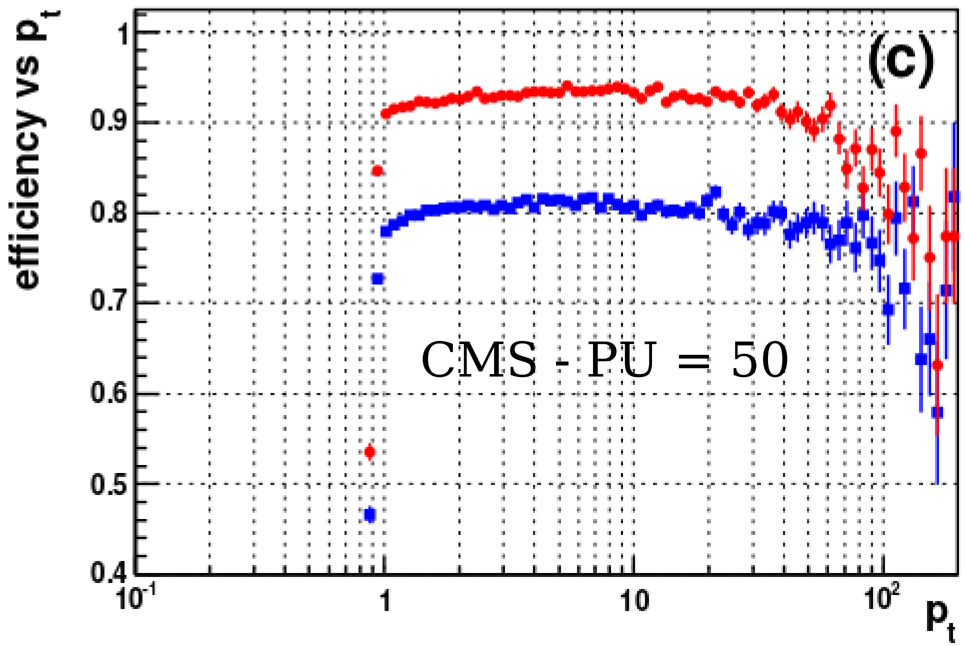
Magnetic Field = 3.8 Tesla

Radius of magnetic field coverage = 1.2 m

Tracking performance and expectations

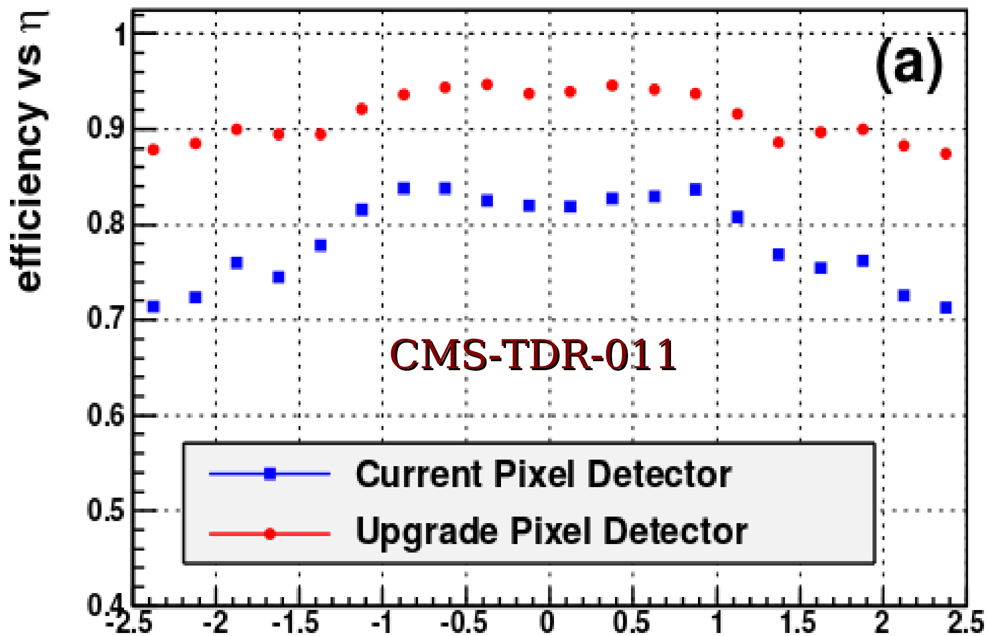
CMS-TDR-011 : http://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf

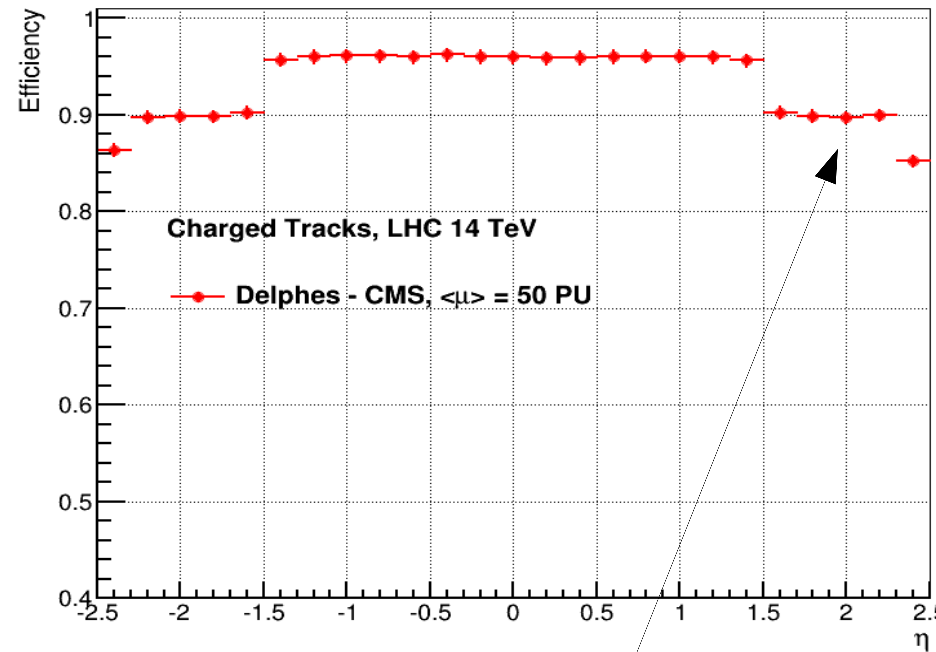




Sample and Conditions		Tracking Efficiency (%)		Track Fake Rate (%)	
Sample	PU/DL/Cuts	Current	Upgrade	Current	Upgrade
Muon	0/No/Cleanup	97.4	98.1	0.0	0.0
Muon	0/Yes/Cleanup	93.9	97.9	0.0	0.0
Muon	50/No/Cleanup	90.1	94.9	0.22	0.17
Muon	50/Yes/Cleanup	81.5	94.4	0.23	0.17

Tracking performance and expectation for Snowmass



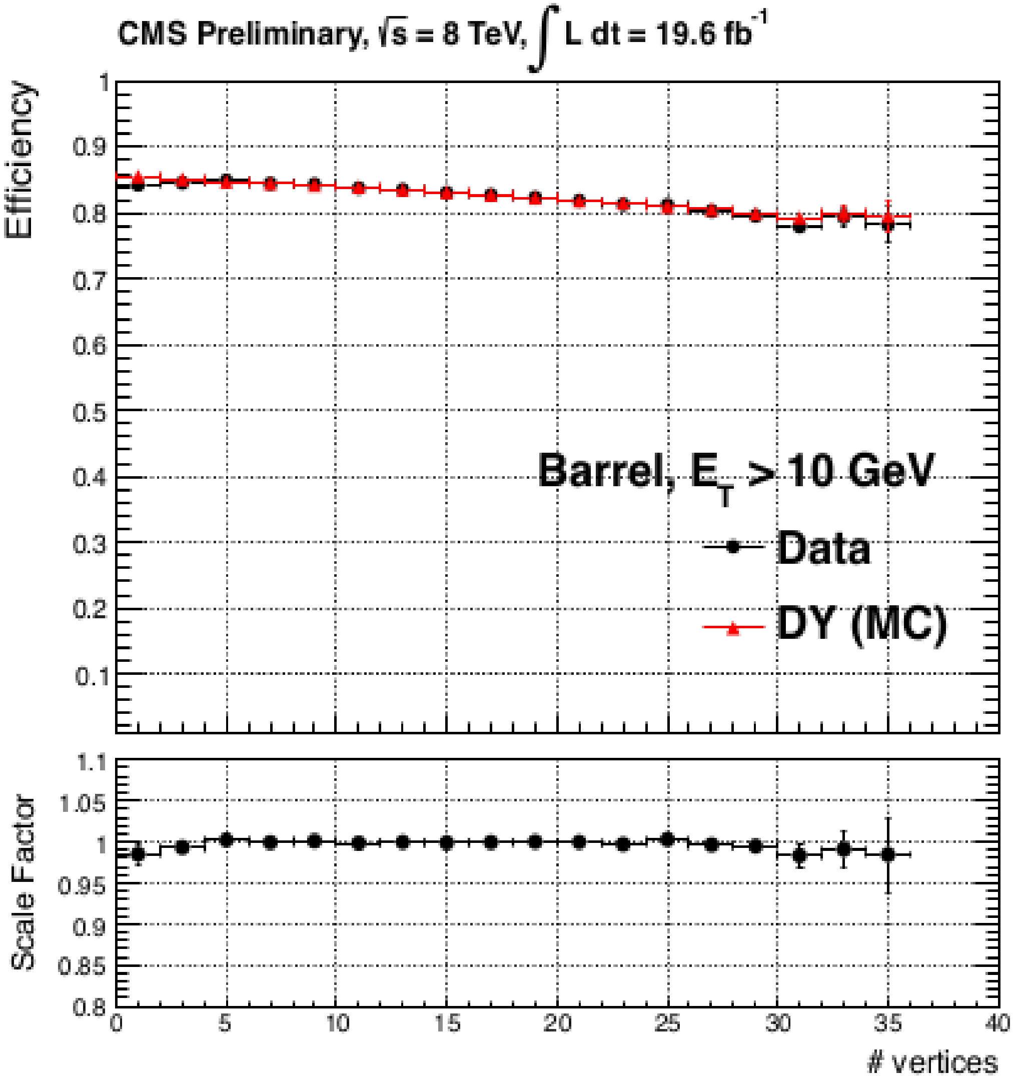


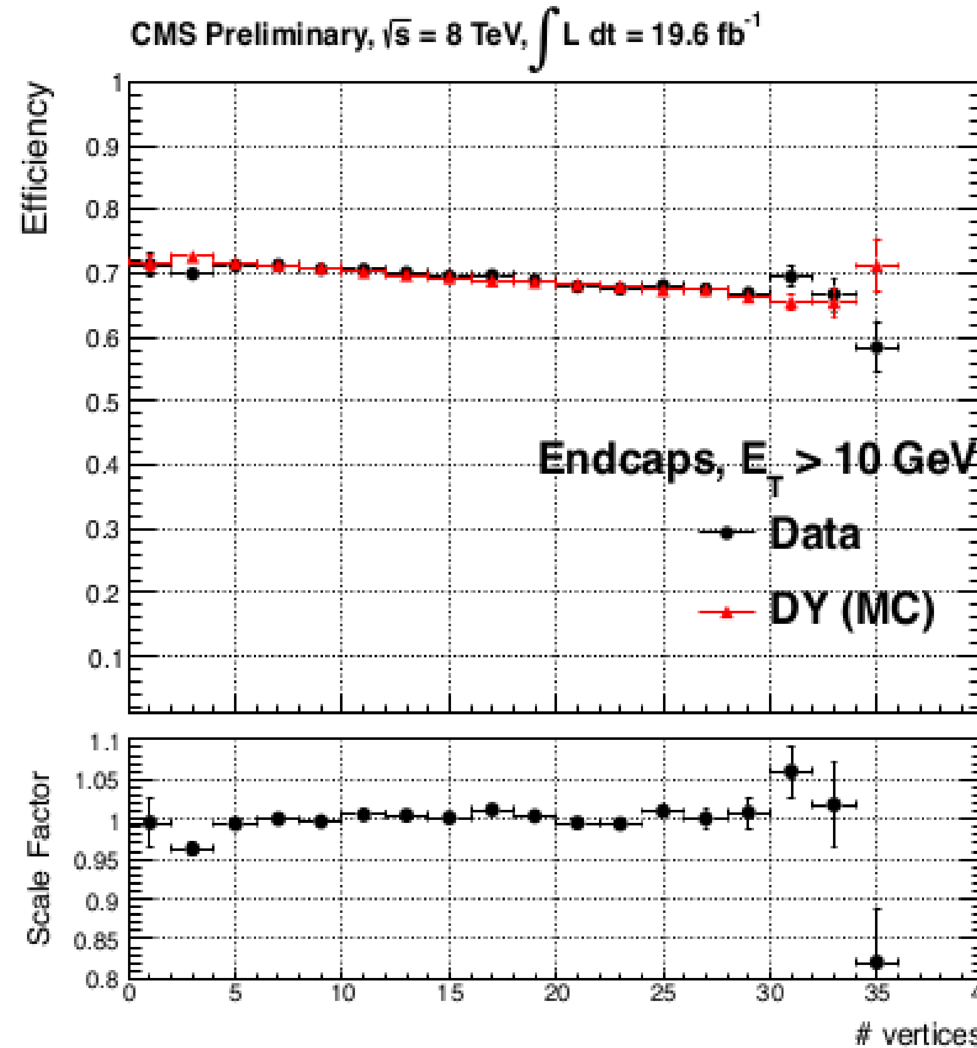
Current proposal to use for tracks:

attribute	ATLAS	CMS	Snowmass
Minimum track p_T to reach calorimeter	0.5 GeV	0.7 GeV	0.6 GeV
Tracking efficiency (DELPHES2)	97%	95%	96%
Muon Efficiency (DELPHES3)	95% / 85%	95% / ~~85%~~	95% / ~~85%~~
Muon Efficiency (upgrade)	95% / 85%	95% / ~~85%~~	95% / ~~85%~~
Electron & Pion Efficiency (upgrade)	95% / 85%	95% / ~~85%~~	95% / ~~85%~~
Momentum resolution @100 GeV (upgrade)	2%	1.5%	1.5%

Electrons (CMS Full Simulation and data)

Electrons (cut based) with medium working point (CMS DP -2013/003)

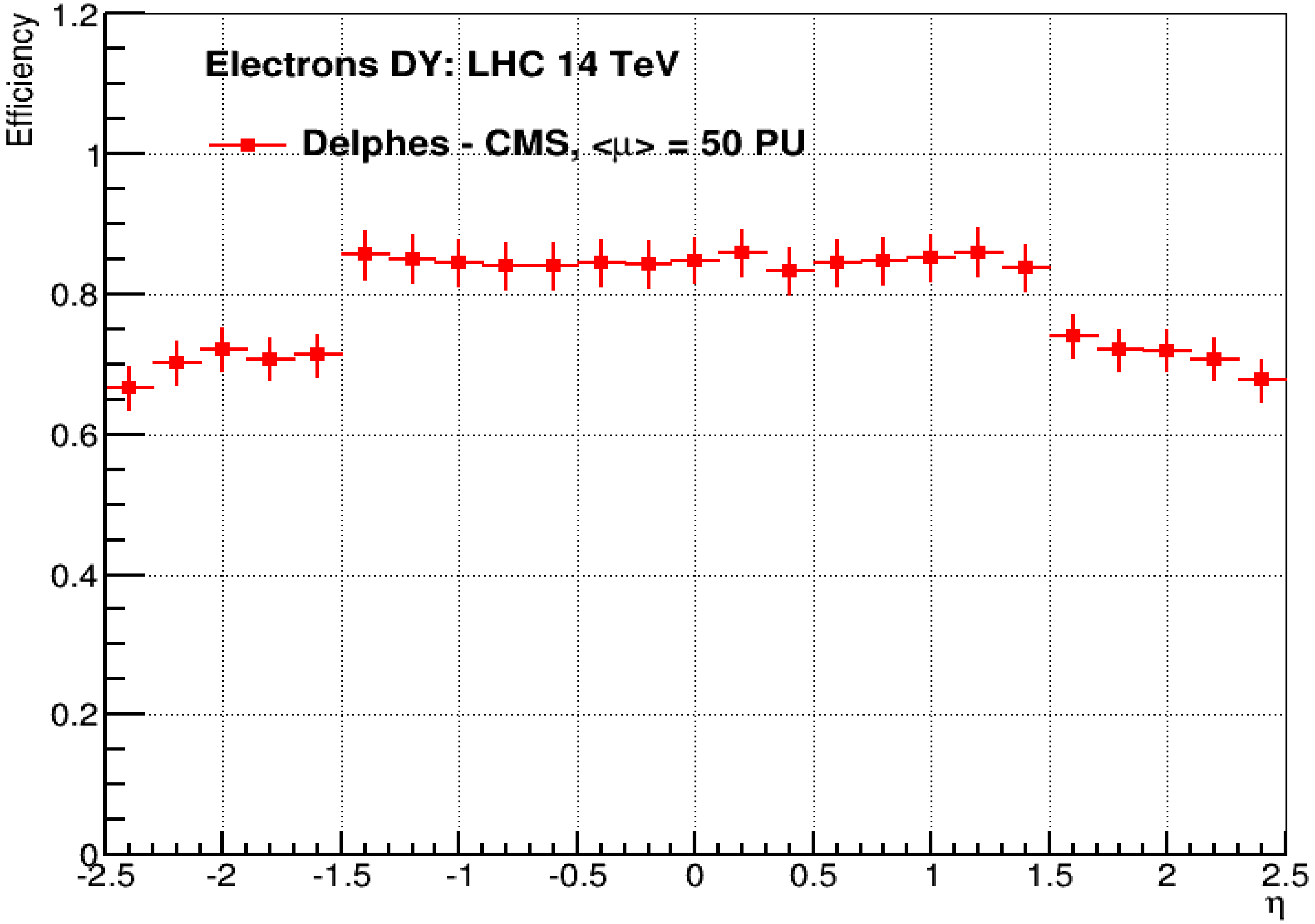




Expected efficiency with 50 PU: ~80% (barrel) and 70% (endcap)

Electrons (Delphes3 with parameterization)

Electrons (cut based) with medium working point (with 50 PU events)

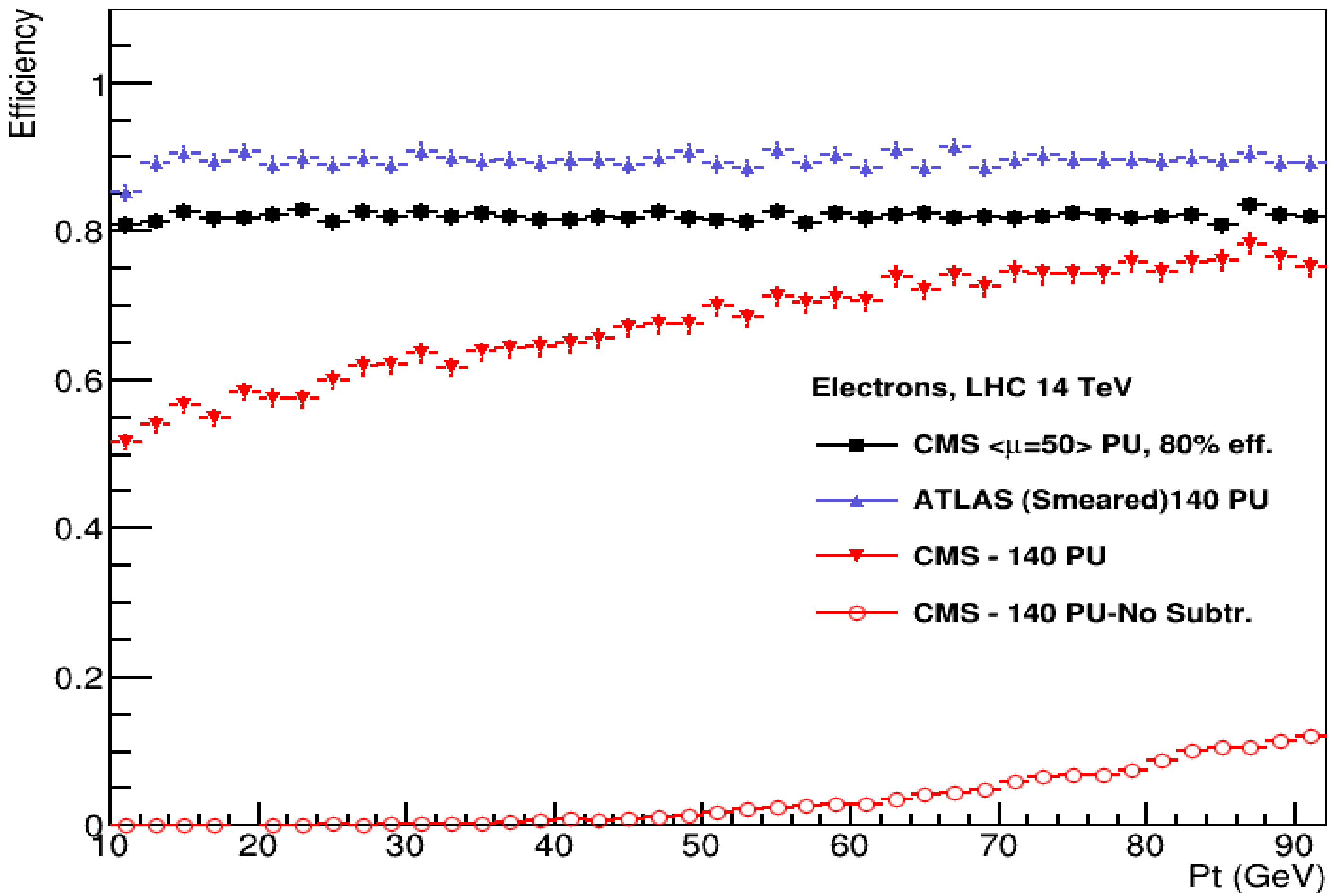


Simulation agrees with the expectations with 50 PU after subtraction.

Proposal: Use this for the combined Snowmass LHC detector

Effects due to additional pileup on electrons

Electrons (cut based) with medium working point (with 50 & 140 PU events)



Assuming 80% “flat” efficiency at 50 Pile-up events:

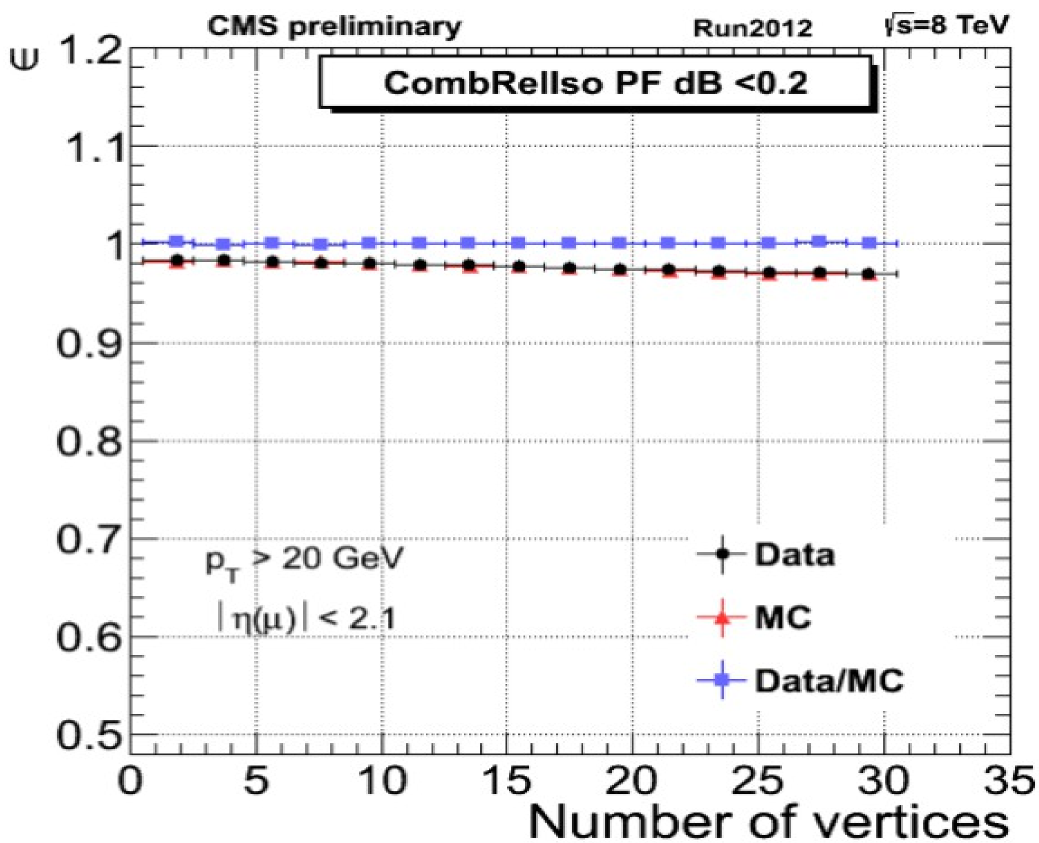
- additional PU events can effect the lepton isolation cone.

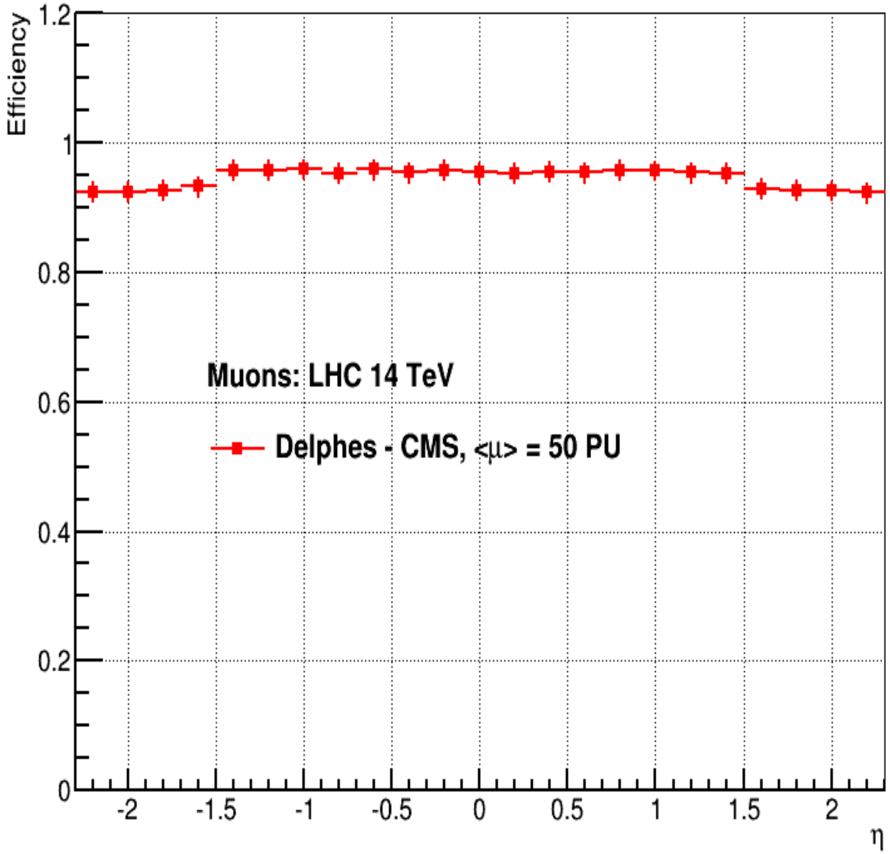
It is important to model the eff. from lepton ID (alone) using fullsim

- the isolation effects can be obtained based on PU/Rho subtraction method.

Muons (CMS Full Simulation comparisons)

CMS DP -2012/025



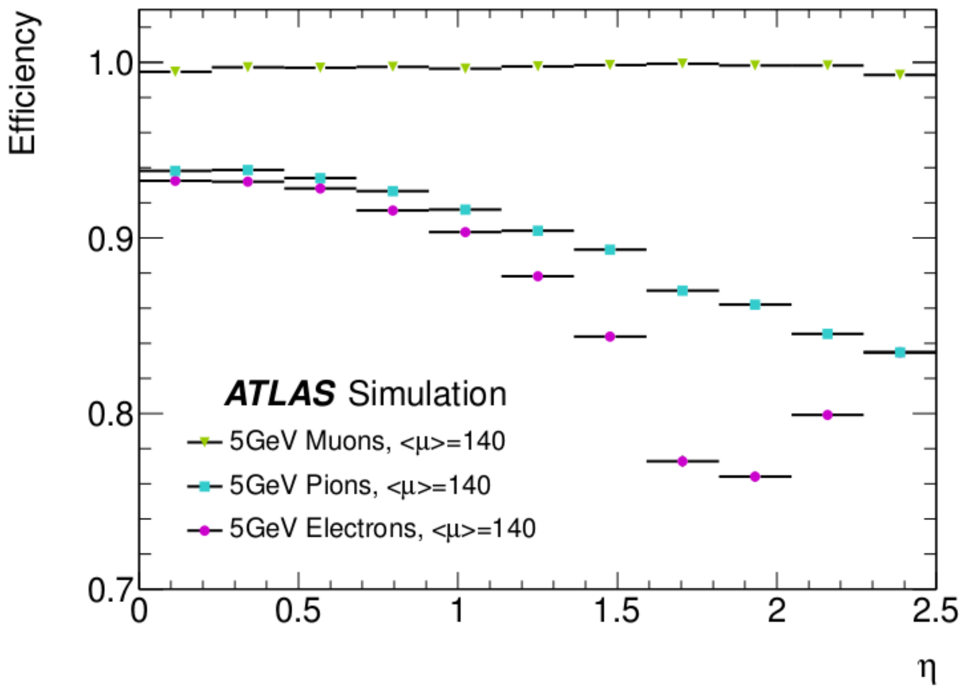


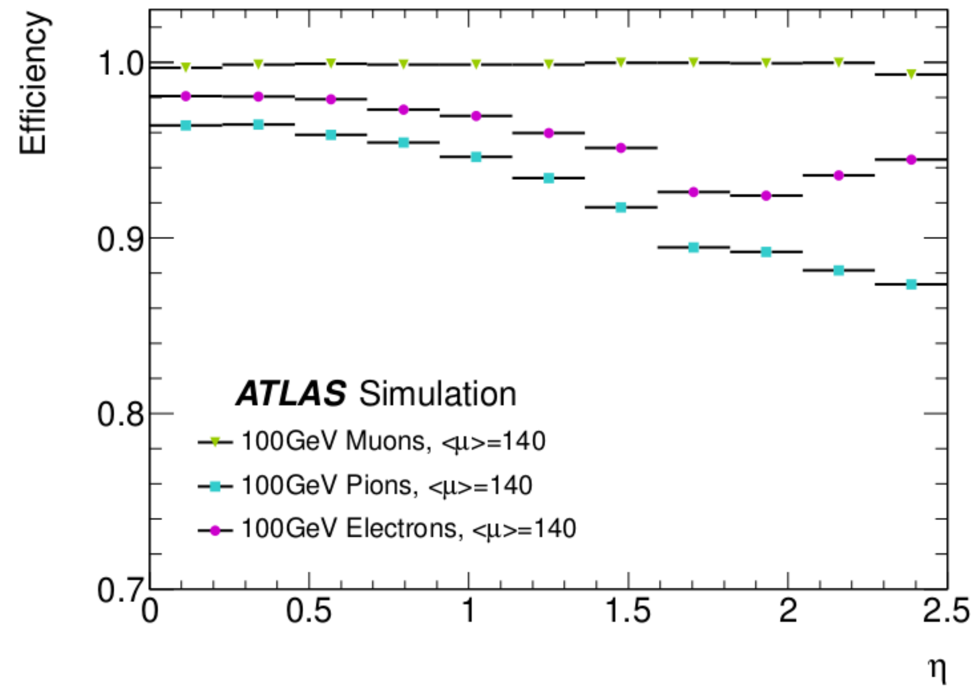
<u>Delphes3 with 50 PUs</u>

Proposal to use: 95% efficiency for muons

- Consistent with CMS ~95% from CMS-TDR-011

ATLAS performance for Electrons/Muons/Tracks





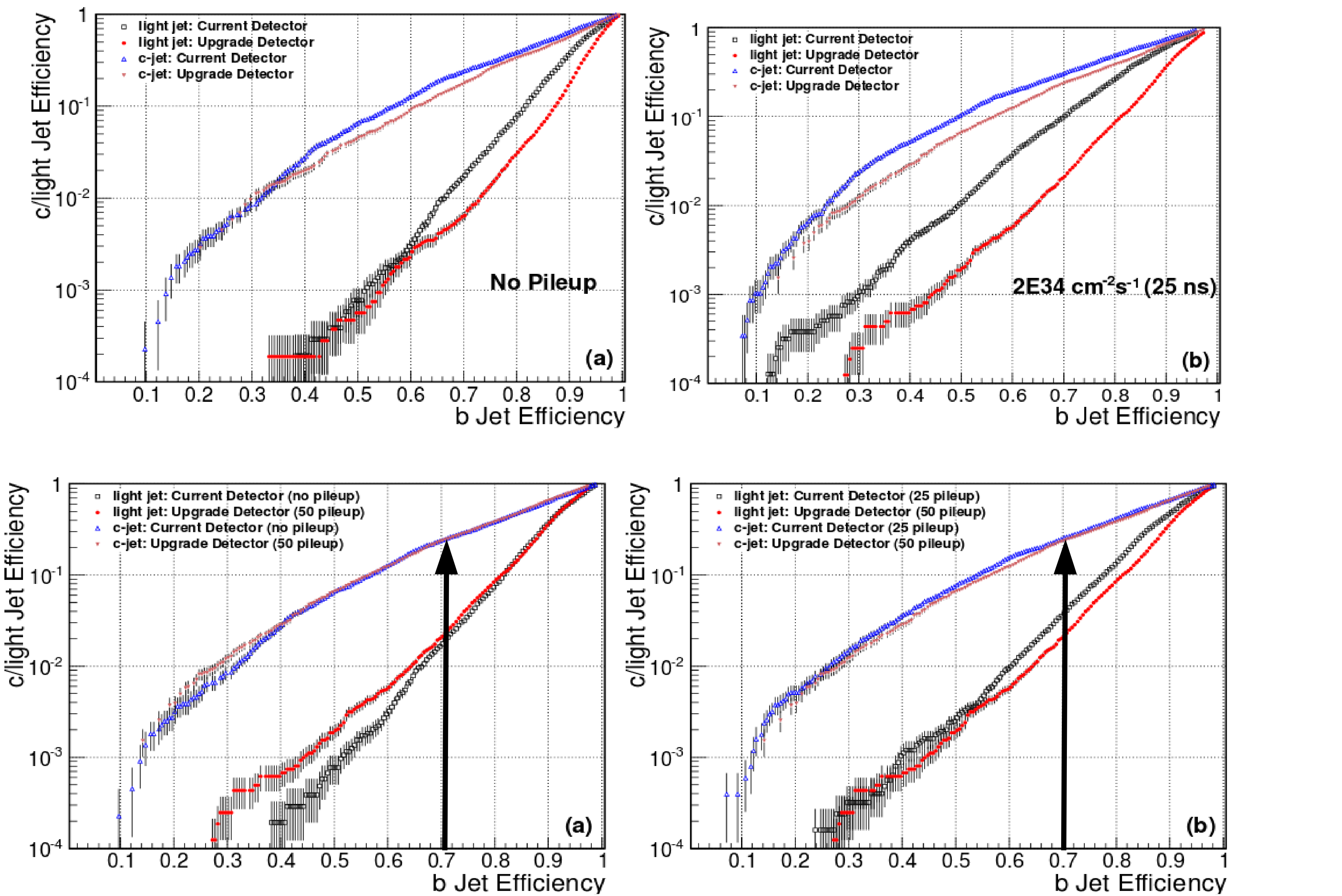
Similar expectation from ATLAS LHCC-I-023 with 140 PU

- Expect ~99% efficiency for muons

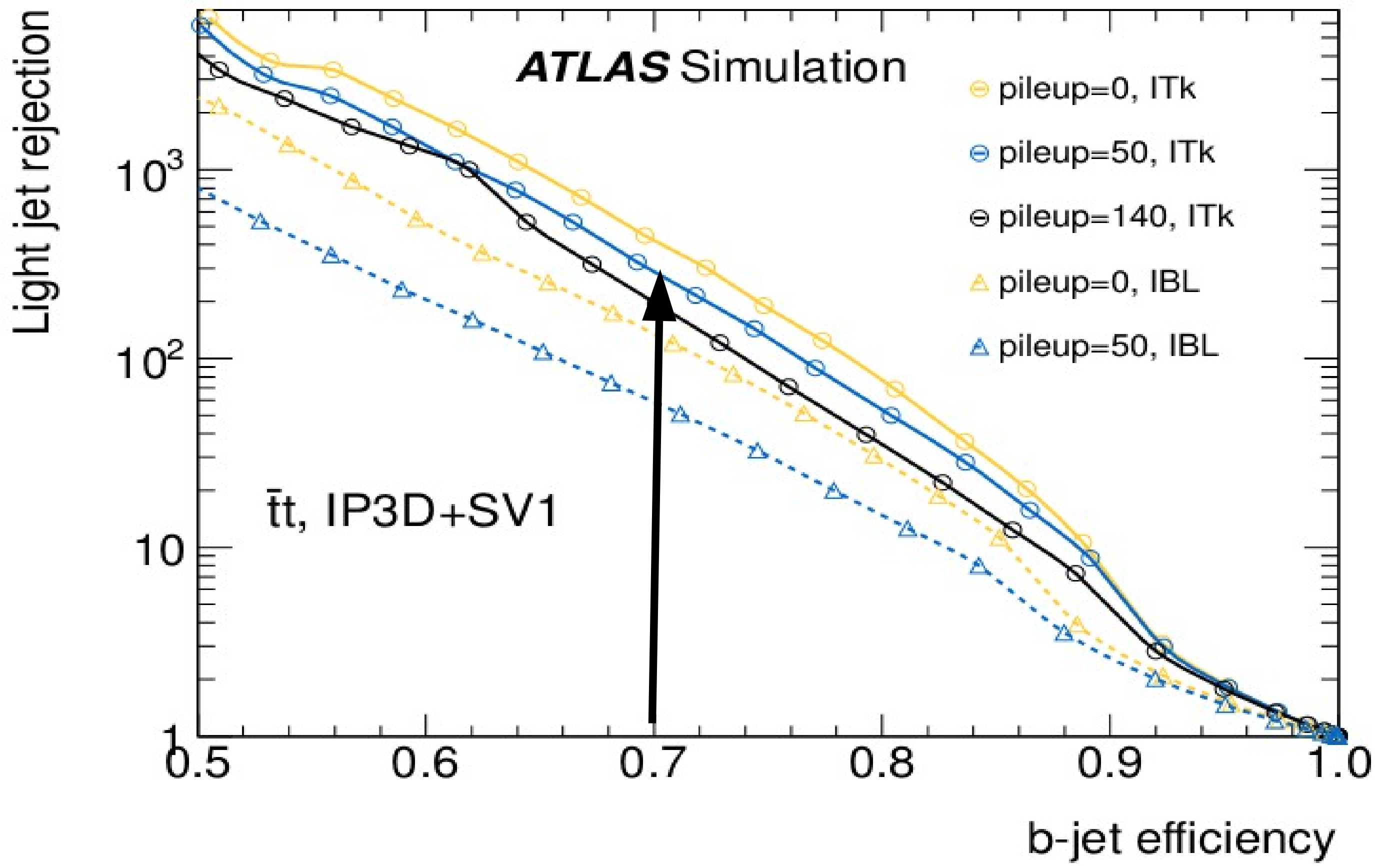
- Expect between: 78% - 94% efficiency for electrons

- Expect between: 84% – 88% efficiency for pions

b-tagged Jets (CMS Upgrade TDR: CMS-TDR-011)

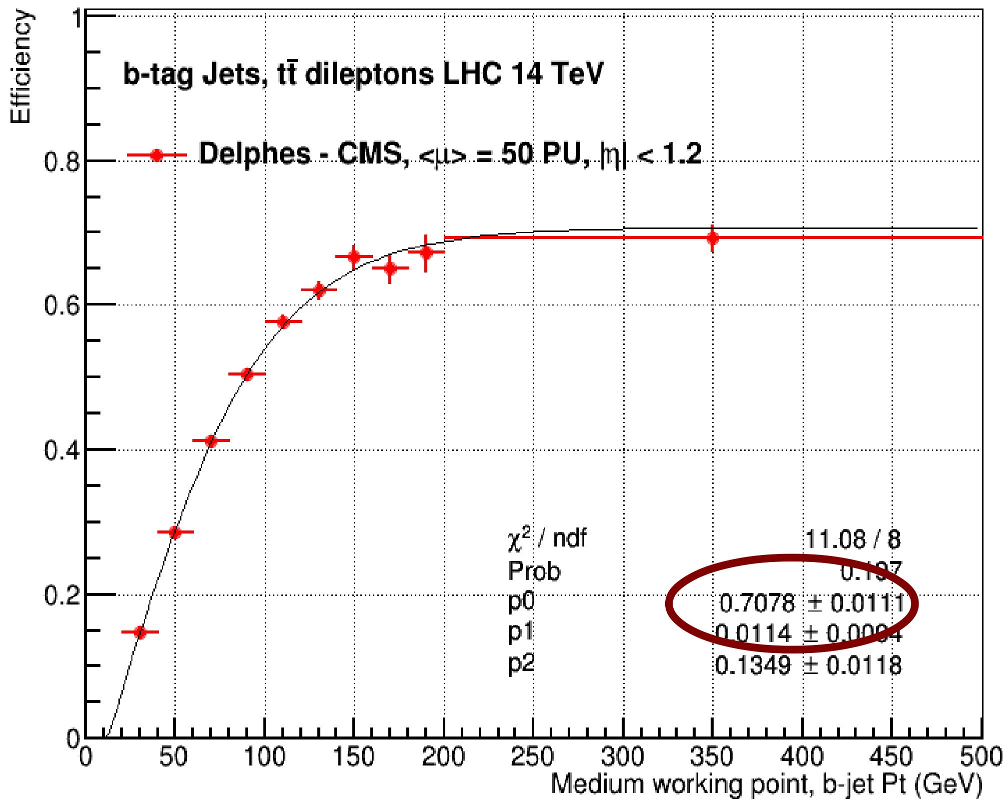


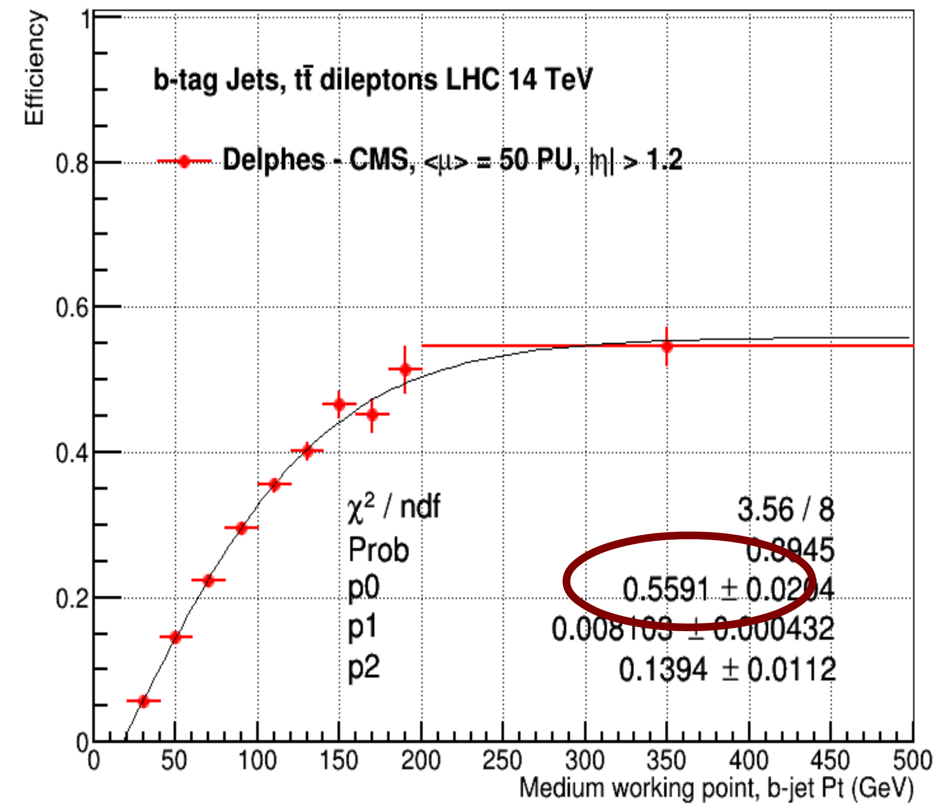
b-tagged Jets (ATLAS LHCC-I-023 - LoI)



attribute	ATLAS	CMS	Snowmass
B tagging efficiency	70 (65) %	70 (65) %	70 (65) %
Charm mistag rate	15%	15%	15%
Light jet mistag rate	2% (1) %	2.5 (1) %	2% (1%)
Light jet mistag rate (upgrade)	0.5 (0.25) %	1 (0.5) %	0.5 (0.25) %

b-tagged Jets (Delphes-3 parameterized simulation)





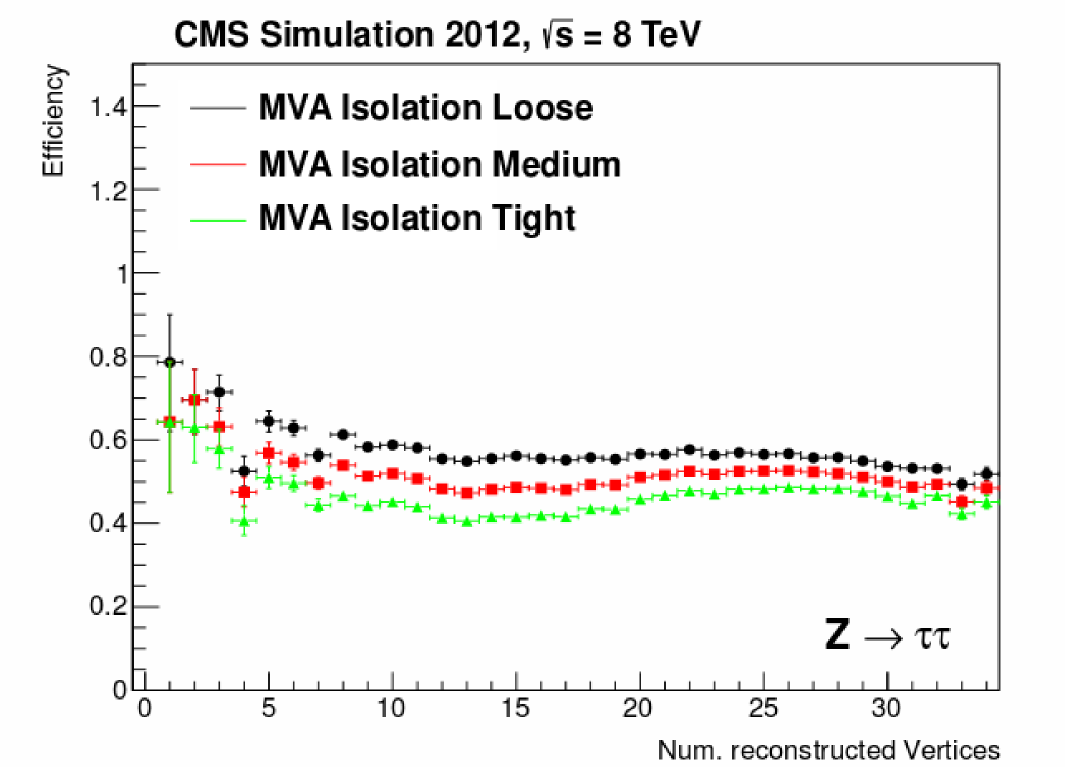
Overall b-tag efficiency: ~65% (barrel and endcap) after pileup subtraction:

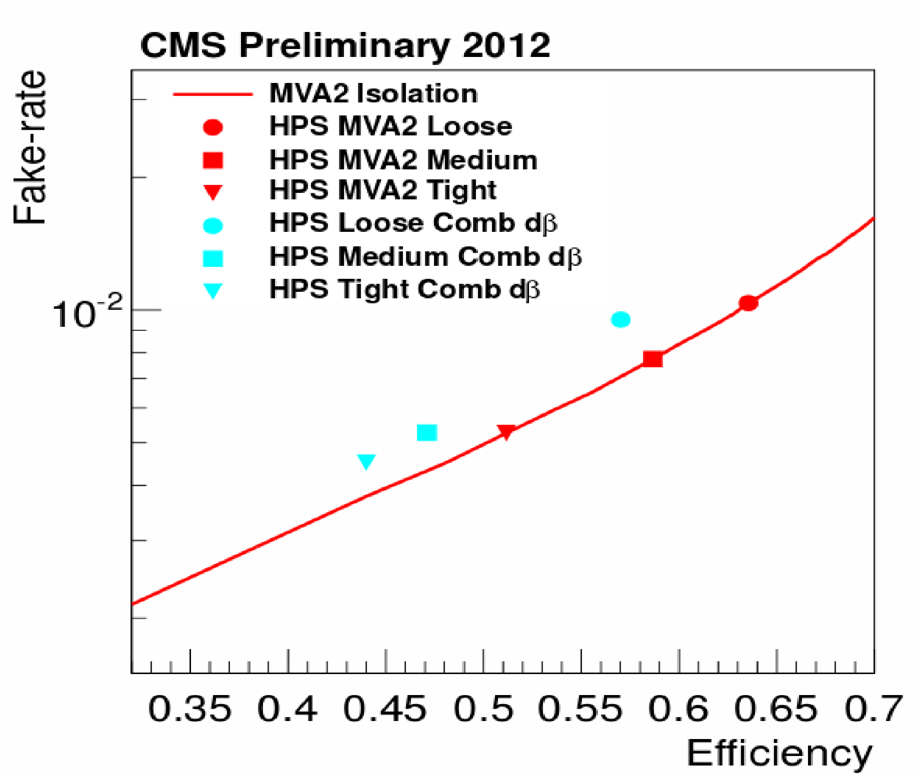
- PU = 50, Mistag = 1%, btag rate = 65%, c-fake ~ 10%

Efficiency in barrel = 70%, Mistag = 1%, c-fake ~ 15%

Efficiency in endcap = 56%, Mistag = 1%, c-fake ~ 15%

Hadronic Tau performance



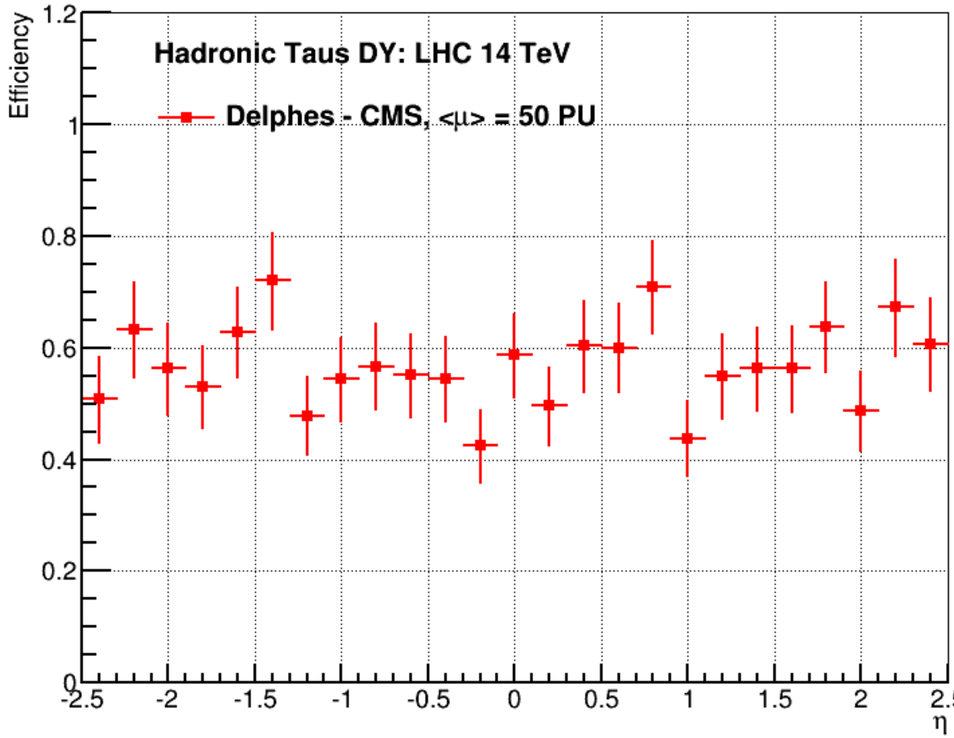


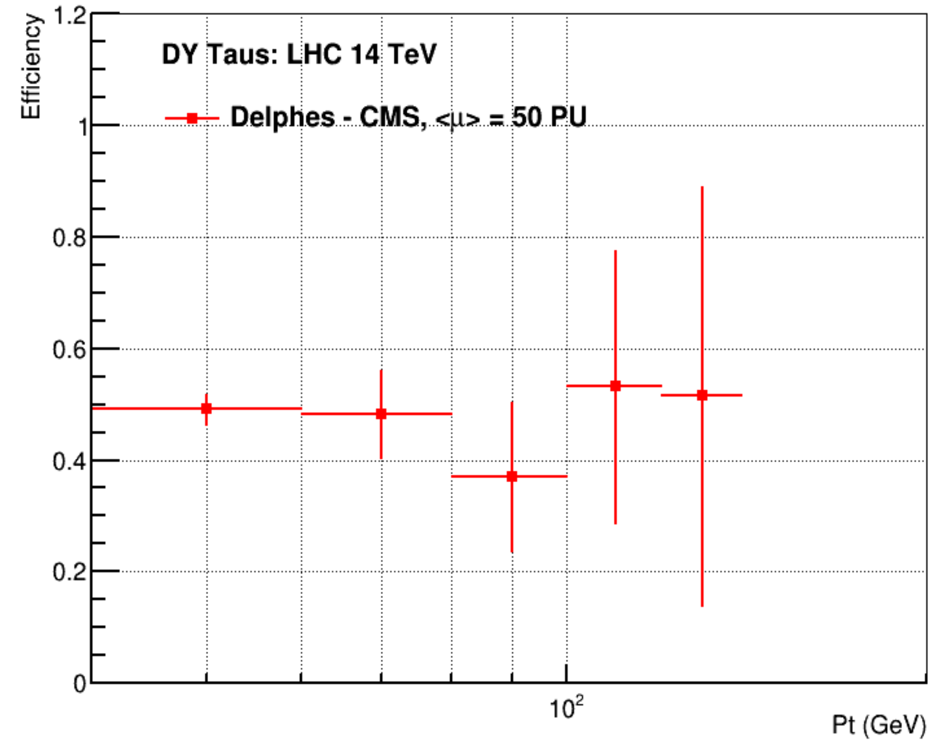
<u>Particle Flow Taus</u>

- Pt (min > 0.5 GeV), |η| < 2.5, dR < 0.15

Proposal: PU = 50, Eff = 50%, Fake Rate = 0.4%

Tau performance (with Delphes3 after parameterization)





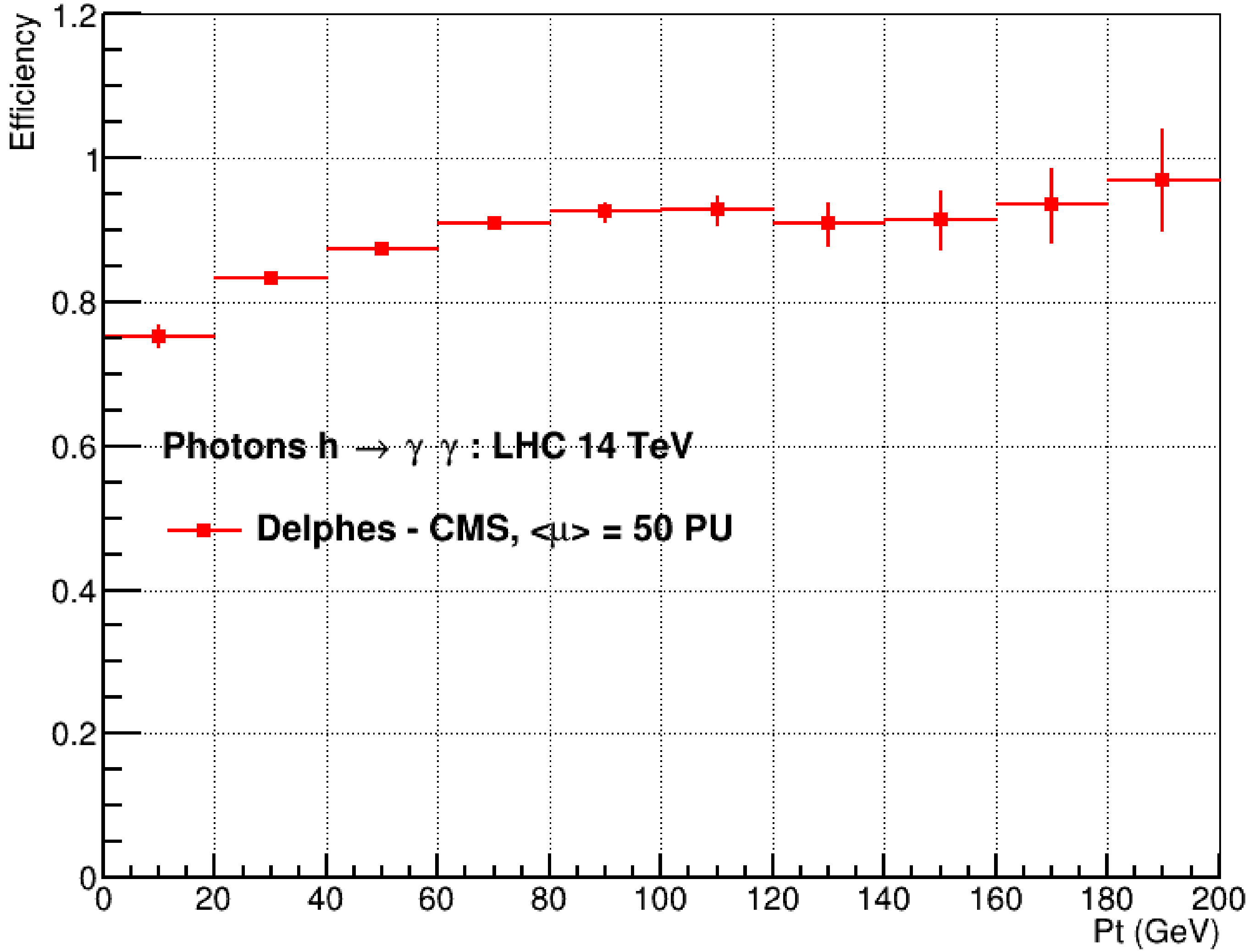
Need higher statistics for hadronic taus.

Delphes3 with 50 PU after subtraction:

- CMS parameterization gives an efficiency of ~ 50%

We expect similar behavior for ATLAS as well.

Photons (Delphes3 using PU and parameterization)

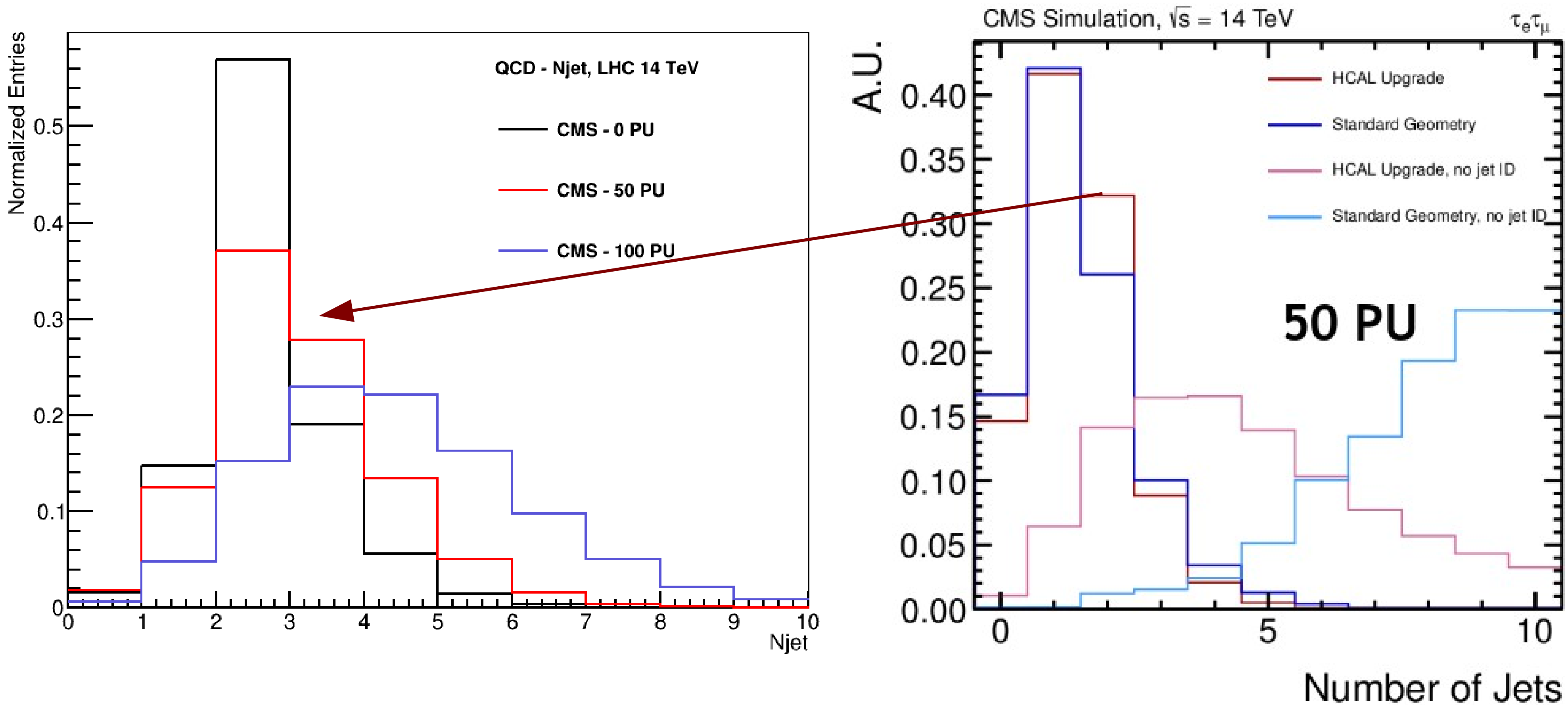


With 50 PU and after subtraction, the proposal for photons is to use:

- Overall efficiency > 80%
- Approx ~ 83% efficiency in barrel

QCD MC events

CMS-TDR-011

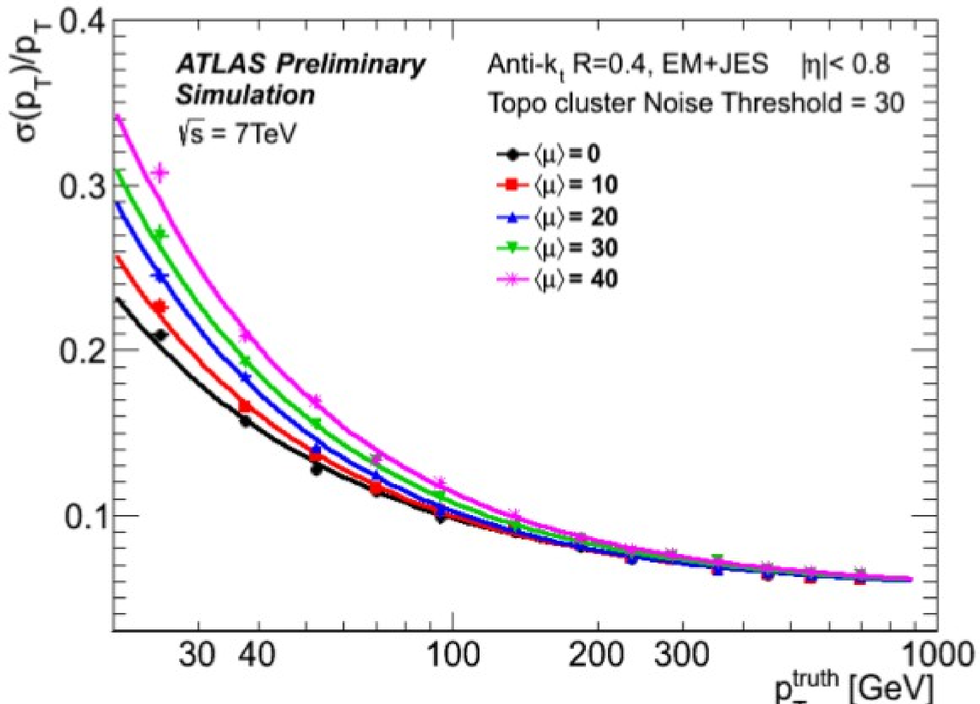


Jet multiplicities increases with increase in PU conditions

- Jet smearing alone cannot produce “new Jets”

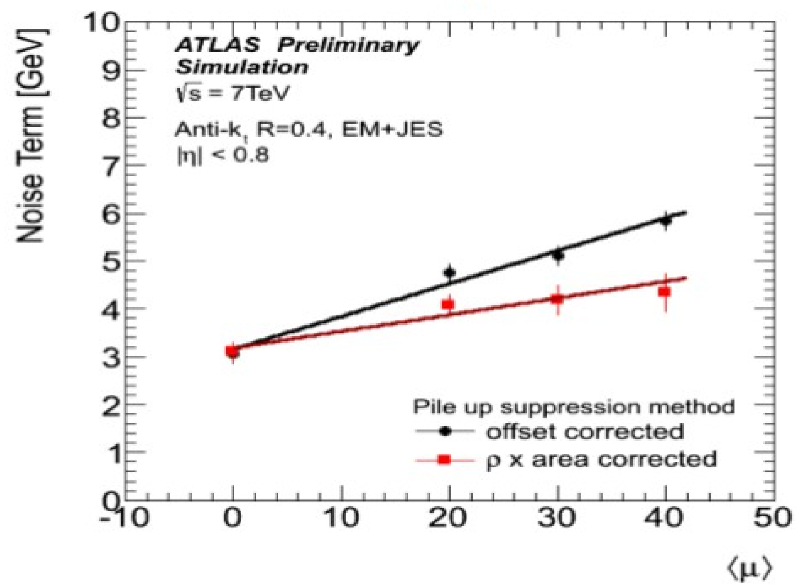
Area subtraction method is even more important for high PU environment

ATLAS jet resolution vs <mu> (full simulation)



$$\frac{\sigma(E)}{E} = \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2}$$

"Noise term"

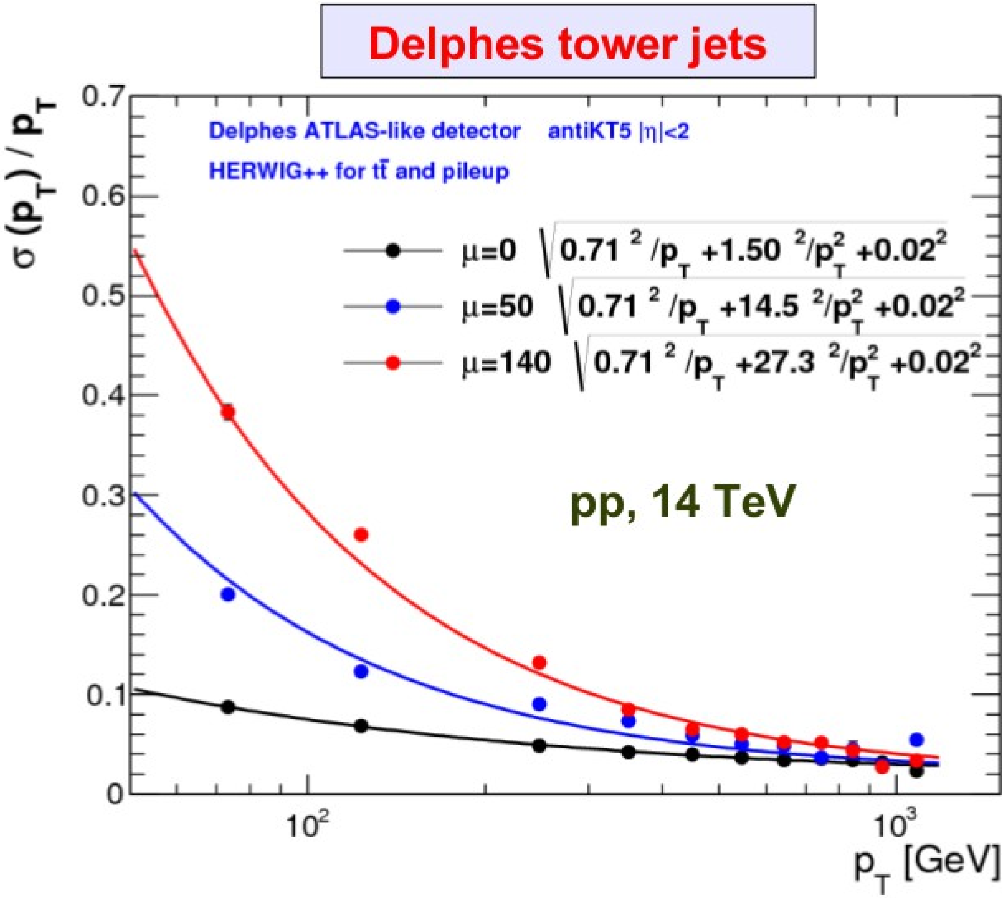


- Keep "sampling" and "constant" terms to be the same when fitting <μ> ≠ 0 cases
- Noise terms increase linearly with <μ>

Extrapolated noise term at <μ> =150:
14 GeV (average offset)
8 GeV (jet area)

Presented by A.Schwartzman at Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013'

Delphes fast simulation. Jet resolution vs <μ>



$$\frac{\sigma(E)}{E} = \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2}$$

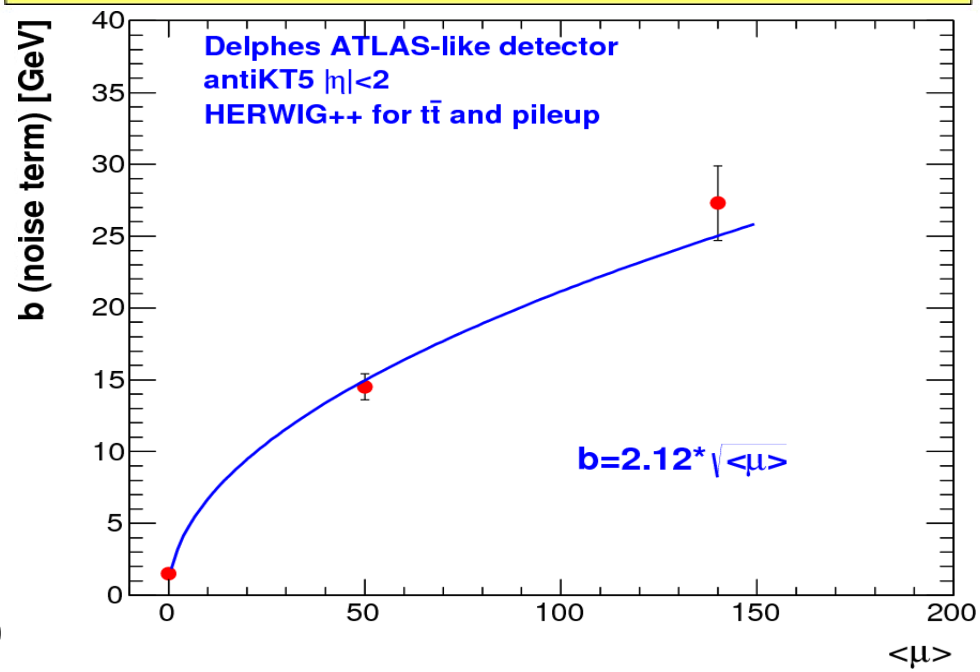
The noise term follow sqrt(μ)

Delphes result agrees with the assumption that pileup mainly changes the noise term ("b")

Noise term ("b") for high-pileup scenario:

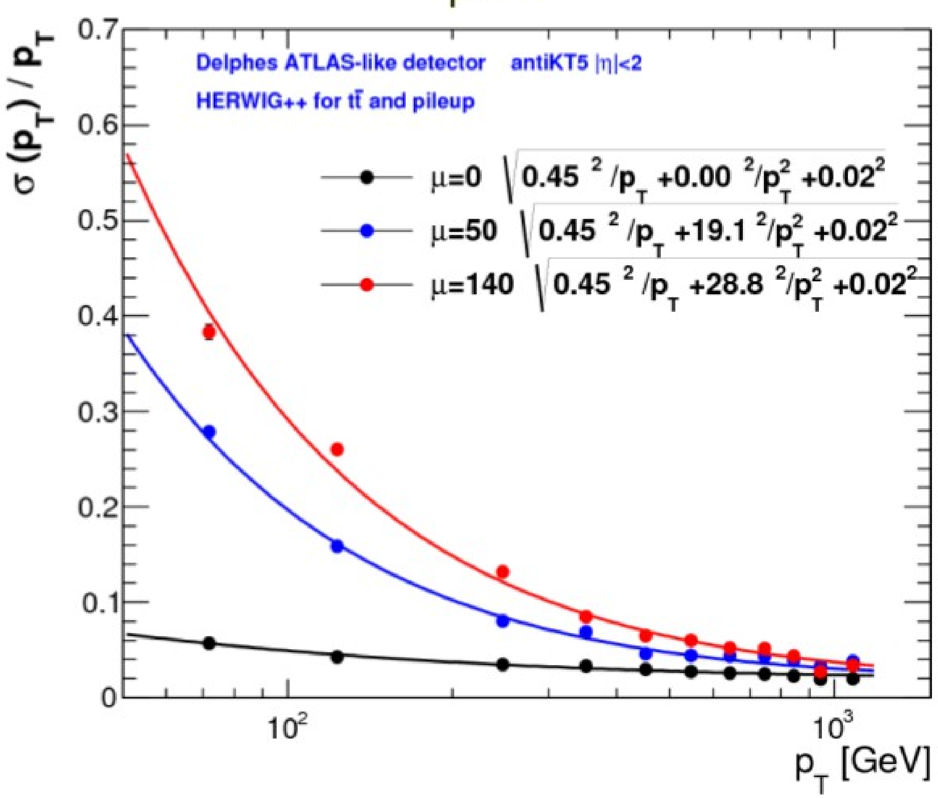
Delphes: b ~ 27 GeV for <μ>~140 for 14 TeV

ATLAS full simulation (extrapolation): b ~14 GeV for <μ>~150 for 7 TeV

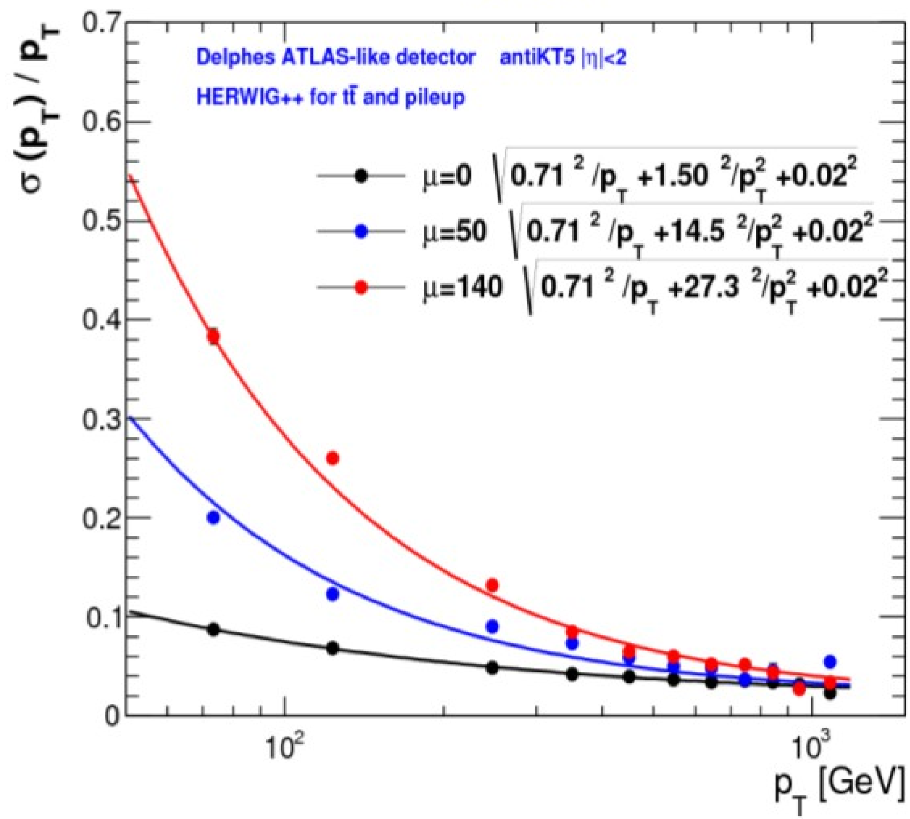


Jet resolution studies

"pflow"



"towers"



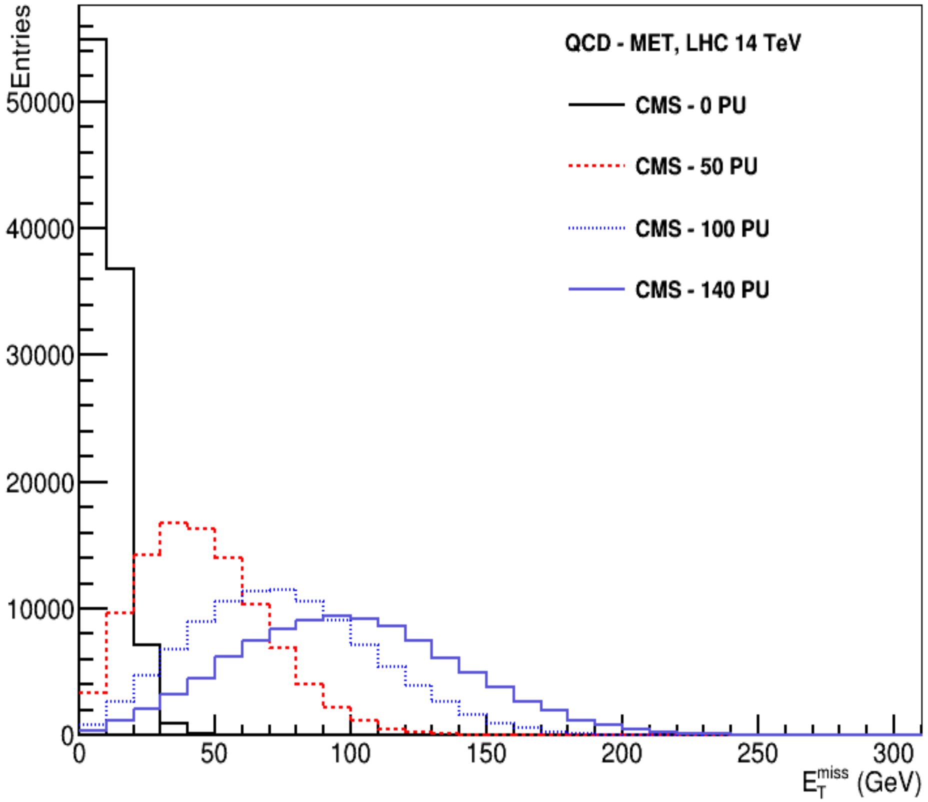
Delphes "pflow" + ATLAS geometry has smaller sampling term than "ATLAS "towers"
The noise term is somewhat larger for the pflow method when $\mu > 0$
Jet resolution for "Towers" and "Pflows" are similar for $\mu > 0$
Performance of pileups subtraction techniques will be essential for proper comparison

For more details see talk by S. Chekanov (ANL) and how jet/sub-jets are effected → On Friday

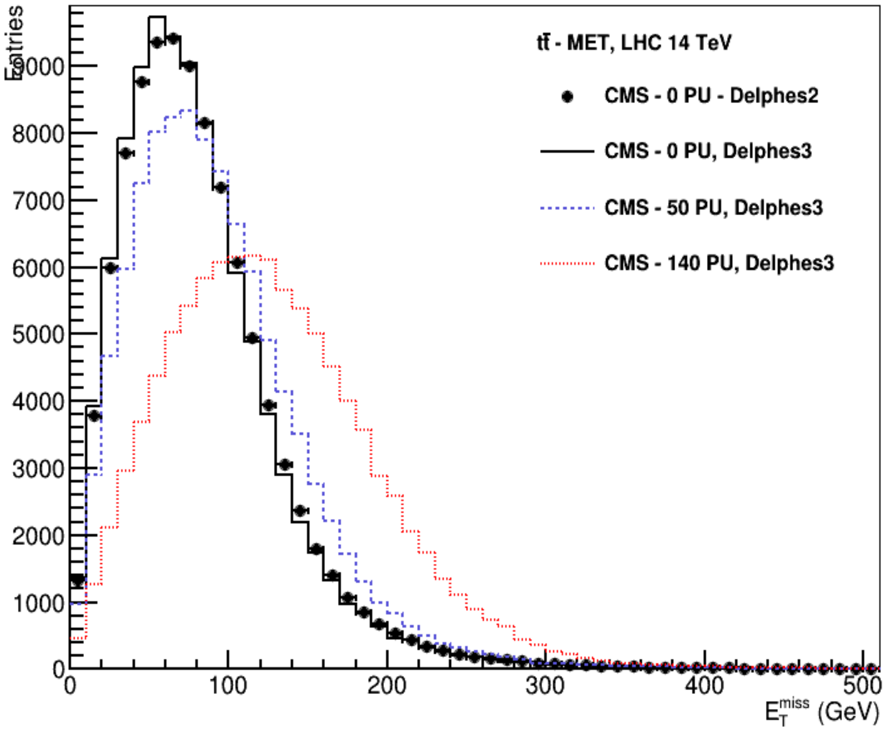
Corrections are needed to recover the expected performance.

Missing transverse momentum

MET from QCD (fake MET)



MET from ttbar (real MET)



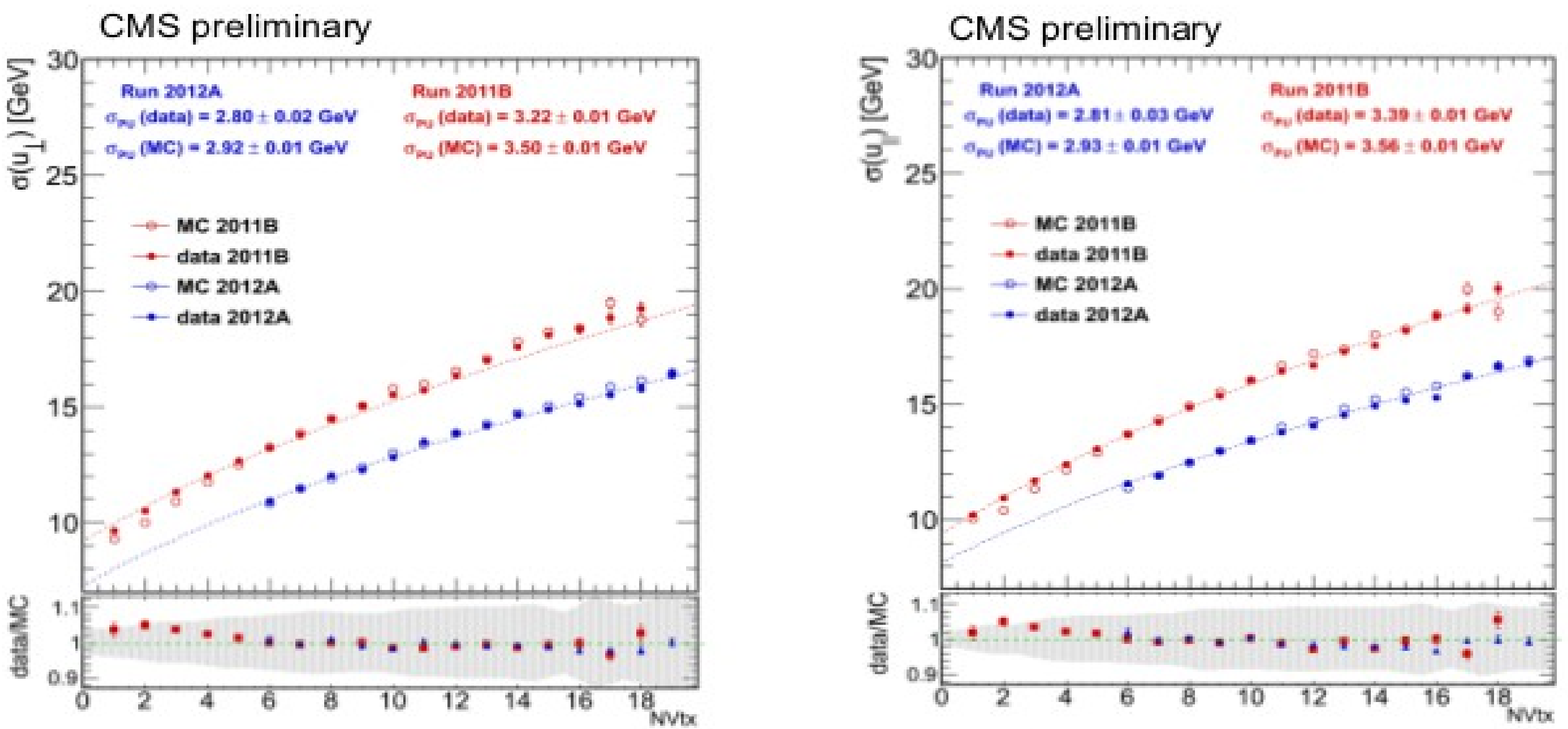
MET is computed using visible objects

- CMS with 50 PU, the effect on real MET is small

- CMS with 140 PU, there is a clear effect on the MET distribution

No MET related corrections have been applied!

Missing transverse momentum



Fit function used : $\sqrt{c^2 + \frac{Nvtx}{0.7} * \sigma_{PU}^2}$

- Resolution for fixed NVtx is better in 2012A due to changes in energy reconstruction
- The distributions are fitted to extract σ_{PU} which represents the degradation in resolution caused by PU events
  - PU introduces an additional smearing of ~2.5-3.5 GeV on MET resolution (in quadrature)
  - The "*c*" component of the fit represents average resolution in events with no PU

Plan to verify the assumptions using Delphes3 with high PU events

Common background generation and simulations

Acknowledgements:

Lothar Bauerdick (FNAL/OSG)

K. Bloom, University of Nebraska for Storage support

BNL & FNAL – For hosting data replication and storage

Common backgrounds and simulations

Major SM backgrounds for Snowmass studies are currently being generated

- We use OSG opportunistic resources to generate Madgraph LHE files
- These will be used with matching and hadronisation from Pythia
- Common Snowmass LHC detector card will be used for PileUp and event reco.

The reconstructed outputs are planned to be transferred to BNL, UNL and FNAL

- Scaling tests are currently underway.
- The outputs can be downloaded via srm, xrootd and http protocols.
- BNL : https://dcdoor10.usatlas.bnl.gov:2881/pnfs/usatlas.bnl.gov/osg/snowmass/
- UNL : http://red-gridftp11.unl.edu/Snowmass
- FNAL : root://cmssrv32.fnal.gov//store/user/snowmass/2013

If you are interested in large background samples or helping to generate the samples

- Subscribe to snowmass-ef-cern (mailing list)
- Or send an email to : meenakshi_narain@brown.edu

Configuration, parameters and framework

Delphes3 package along with detector cards with pile-up will be centrally available

Currently hosted at: http://cmssw.cvs.cern.ch/cgi-bin/cmssw.cgi/UserCode/Delphes/

Additional interactions (or pile-up events) are mixed during the simulation/reco:

```
module PileUpMerger PileUpMerger {
  set InputArray Delphes/stableParticles
  set OutputArray stableParticles
  # pre-generated minbias input file
  set PileUpFile "MinBias.pileup"
  # average expected pile up
  set MeanPileUp 140
  # spread in the beam direction in m (assumes gaussian)
  set ZVertexSpread 0.05
  # Z vertex resolution in m
  set ZVertexResolution 0.0001
}
```

Input file with Minbias events

Z spread in meters

Z spread resolution in meters

MinBias events in pileup (mixing) format will also be centrally hosted.

Currently available only at CERN:

- for 13 TeV LHC: /eos/cms/store/user/spadhi/13TeV/MinBias13TeV.pileup
- for 33 TeV LHC: /eos/cms/store/user/spadhi/33TeV/MinBias33TeV.pileup

How to run Snowmass configuration without pile-up

- Download you favorite physics generator or Madgraph for SM processes.
- Run the generator to obtain LHE files
- Hadronize them with Pythia or Herwig with final output in hepmc/Stdhep format
- Download Delphes3 from the central location with configurations (with/without PU)

Running Delphes with HepMC input files:

```
./DelphesHepMC examples/delphes_card_CMS.tcl output.root input.hepmc
```

Running Delphes with STDHEP (XDR) input files:

```
./DelphesSTDHEP examples/delphes_card_CMS.tcl delphes_output.root input.hep
```

Running Delphes with LHEF input files:

```
./DelphesLHEF examples/delphes_card_CMS.tcl delphes_output.root input.lhef
```

Running Delphes with files stored in CASTOR:

```
rfcat /castor/cern.ch/user/d/demine/test.hepmc.gz | gunzip | ./DelphesHepMC examples/delphes_card_CMS.tcl delphes_output.root
```

Running Delphes with files accessible via HTTP:

```
curl http://cp3.irmp.ucl.ac.be/~demin/test.hepmc.gz | gunzip | ./DelphesHepMC examples/delphes_card_CMS.tcl delphes_output.root
```

How to run Snowmass configuration with pile-up

- Download you favorite physics generator or Madgraph for SM processes.
- Run the generator to obtain LHE files
- Hadronize them with Pythia or Herwig with final output in hepmc/Stdhep format
- Download Delphes3 from the central location with configurations (with pile-up)
- Download the MinBiasX.pileup file from the central location

Run Delphes on your sample X with pile-up:

```
./DelphesSTDHEP examples/delphes_card_CMS_PileUp.tcl X_PileUp.root X.hep
```

Pile-up subtraction

Since charged particles have already been subtracted to some extent, pile-up contamination only affects the jet energy resolution and the lepton/photon isolation.

- Jet pile-up subtraction is done via the `JetPileUpSubtractor` module that takes as input the jet collection and rho:

```
set JetInputArray FastJetFinder/jets
set RhoInputArray rho
```

- Isolation subtraction is done inside the `Isolation` module itself just by adding the line in the delphes card:

```
set RhoInputArray rho
```

Common backgrounds and simulations

Statistics of event samples generated so far:

Background samples	13 TeV LHC (events)	33 TeV LHC (events)
ttbar+Jets(0-4)	~50 M	~ 40 M
W + Jets (0-4)	~25 M	~ 40 M
Z + Jets (0 -4)	~5 M	< 10 M
WW+Jets (0-2)	~ 10 M	~ 40 M
WZ+Jets (0-2)	~ 10 M	~ 20 M
ZZ + Jets (0 – 2)	~ 20 M	~ 40 M
WPhoton + Jets (0-2)	~ 20 M	~ 20 M
ZPhoton + Jets (0-2)	~ 20 M	~ 20 M
Photon + Jets (0-4)	~ 20 M	~ 20 M
Di-Photon+Jets (0-2)	~ 20 M	~ 20 M

https://twiki.cern.ch/twiki/bin/view/CMSPublic/NPSnowmass2013Samples

Index of /Snowmass

http://red-gridftp11.unl.edu/Snowmass

[ICO]	Name	Last modified	Size	Description
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Apache/2.2.15 (Scientific Linux) Server at red-gridftp11.unl.edu Port 80

https://twiki.cern.ch/twiki/bin/view/CMSPublic/NPSnowmass2013Samples

Examples on pileup mixing and event generation

```
#Setup environment
#Get Madgraphh and install Pythia
wget http://launchpad.net/madgraph5/trunk/1.5.0/+download/MadGraph5_v1.5.8.tar.gz --no-check-certificate
tar -xzf MadGraph5_v1.5.8.tar.gz
cd MadGraph5_v1_5_8
./bin/mg5
mg5> install pythia-pgs
mg5> quit
cd ..

#Get Delphes 3 and compile
wget http://cp3.irmp.ucl.ac.be/downloads/Delphes-3.0.5.tar.gz
tar -xzf Delphes-3.0.5.tar.gz
cd Delphes-3.0.5
make
cd ..

#Get Delphes cards and put Pythia card where it is expected
cvs co UserCode/Delphes
#When Pythia runs it expects to find pythia_card.dat in a Cards directory up one from the run directory
ln -s UserCode/Delphes Cards

#Run Pythia
mkdir run
cd run
wget http://home.fnal.gov/~jstupak/files/TTJets_MassiveBinDECAY_8TeV-madgraph_0.lhe
#Pythia expects to run on an input file named unweighted_events.lhe
mv TTJets_MassiveBinDECAY_8TeV-madgraph_0.lhe unweighted_events.lhe
../MadGraph5_v1_5_8/Template/bin/internal/run_pythia ../MadGraph5_v1_5_8/pythia-pgs/src

#Run Delphes 3
../Delphes-3.0.5/DelphesSTDHEP ../Cards/CMSDetectorCard_delphes3_PU50.tcl delphes3.root pythia_events.hep
```

Tutorial : http://home.fnal.gov/~jstupak/files/delphesTut.pdf

Thoughts on expected increase in pileup interactions

Thoughts on expected increase in pileup interactions

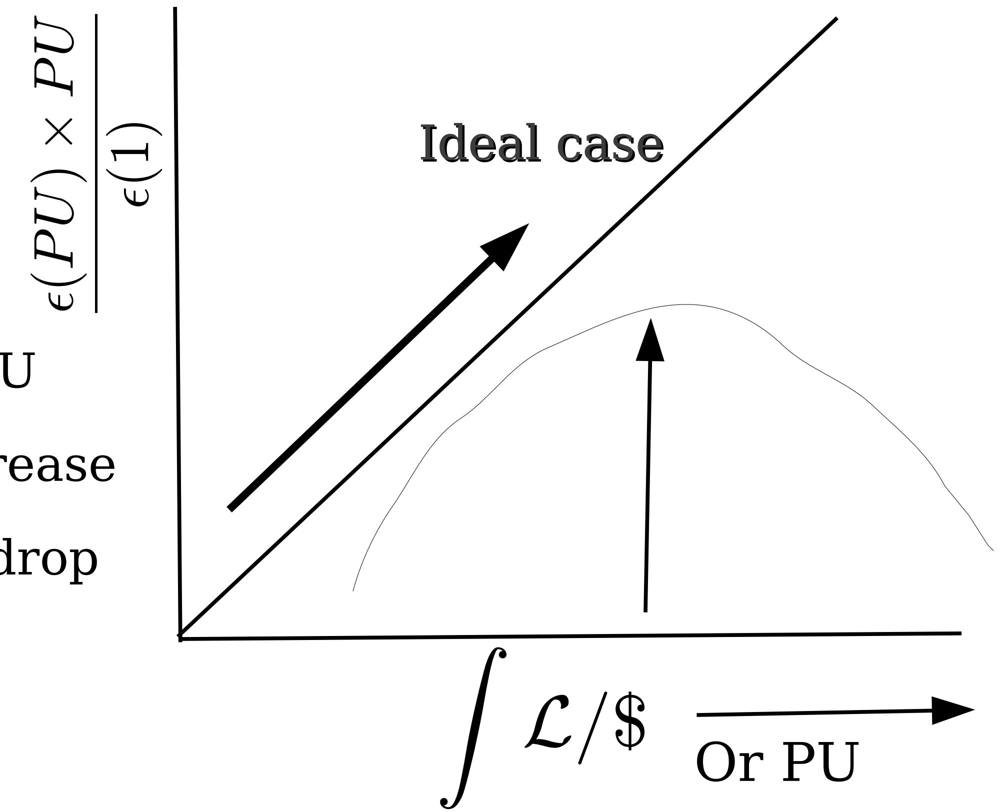
As we know PU is proportional to the instantaneous luminosity

$$PU = \alpha\mathcal{L}; \int \mathcal{L} = \underbrace{k \times year}_{\text{Constant}} \times PU$$

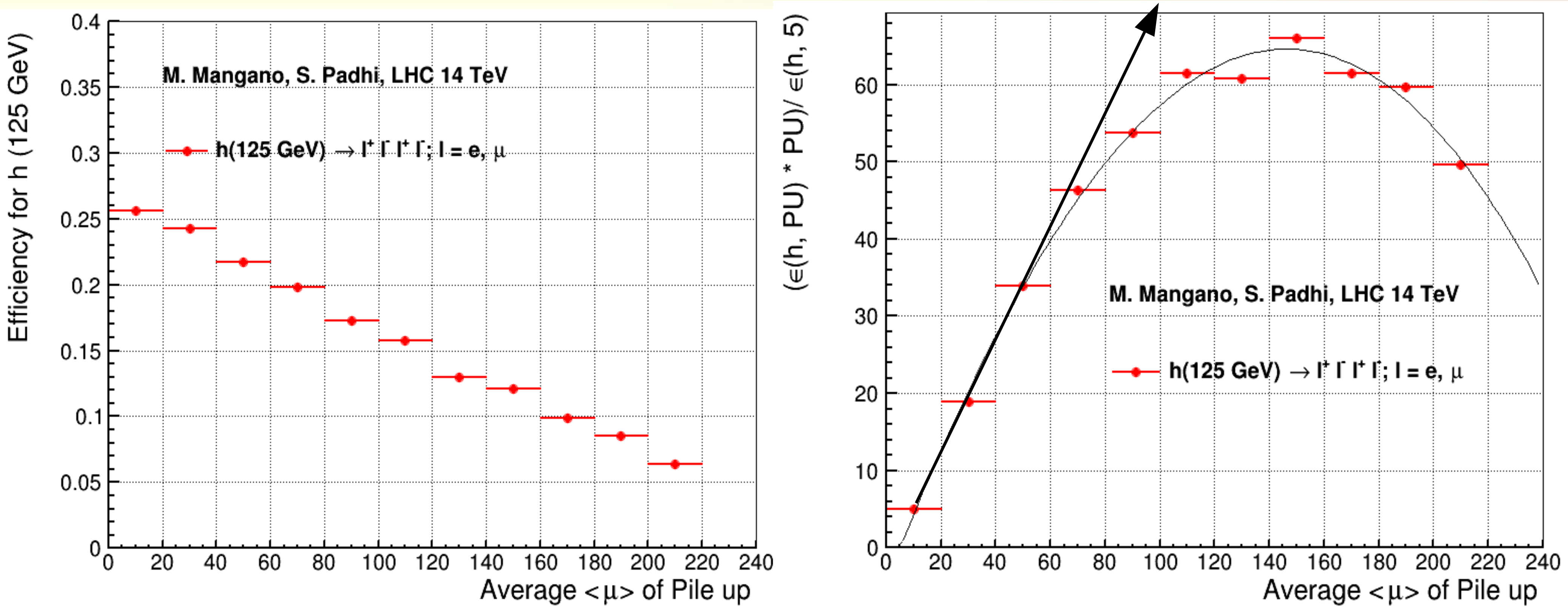
$$N_{ev} = \int \mathcal{L} \times \sigma \times \epsilon(PU)$$

<u>For example Higgs → 4 leptons studies:</u>

- We want best efficiency with increase in PU
- Or largest number of events with lumi increase
- At some stage with added PU the eff. will drop
- It is better to stay with increase in slope



Thoughts on expected increase in pileup interactions



Reconstruction efficiency for h → 4lept., goes down with increase in PU

- It is safer to stay below PU ~ 150, else there is no gain with increase in lumi

Assuming the "charged tracks" coming from non-primary vertex events will be vetoed

The tracker can mitigate the effects of pile-up interactions

- but it cannot help with neutrals.

Is there a way to mitigate Calorimeter pile-up? Or even correct the slope?

One of the goals of the picosec timing calorimeters would be to associate photon deposits to separate vertices. See long term studies by Marcello Mannelli (CERN)

Summary and Conclusion

LHC

Rolf Heuer CERN-DG, January 2013

Key message

There is a program at the energy frontier with the LHC for the next ~20 years:

13, then 14 TeV, design luminosity
14 TeV high luminosity (HL-LHC)

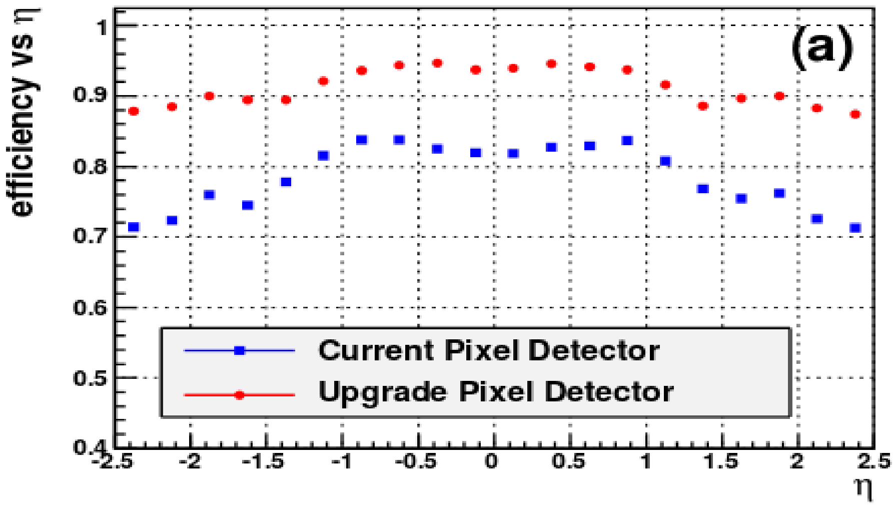
The Energy and Intensity Frontiers Meet

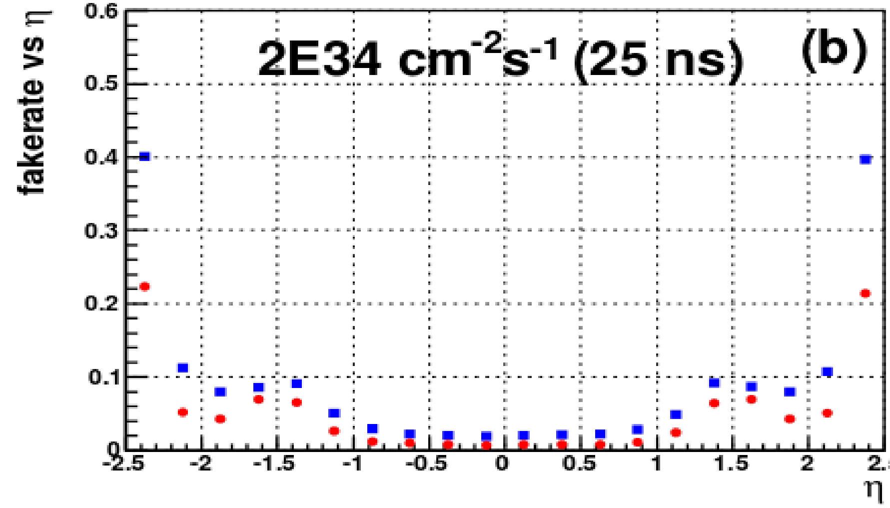
The studies are done using resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science.

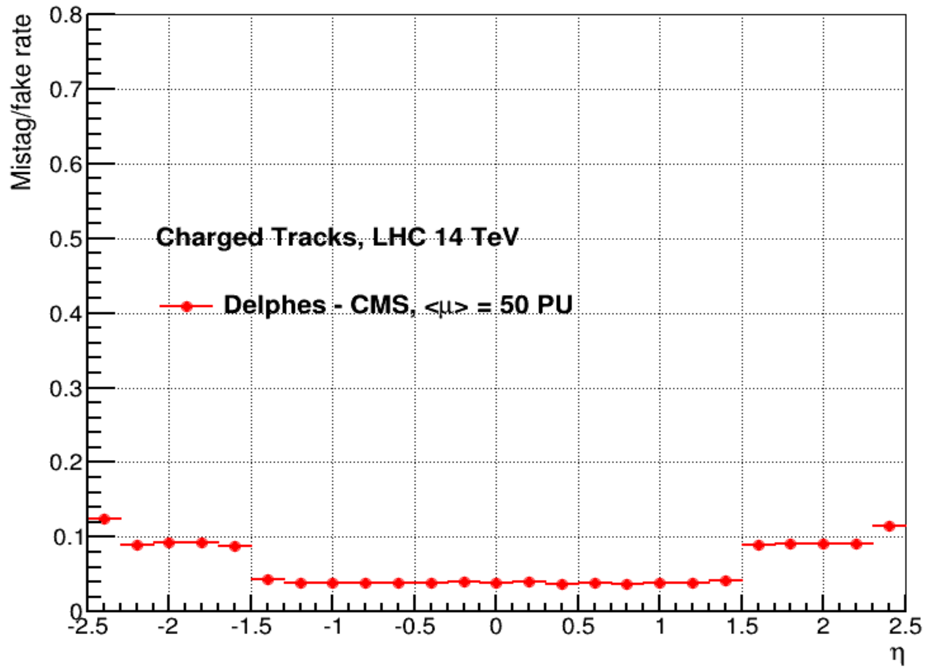
Backup slides

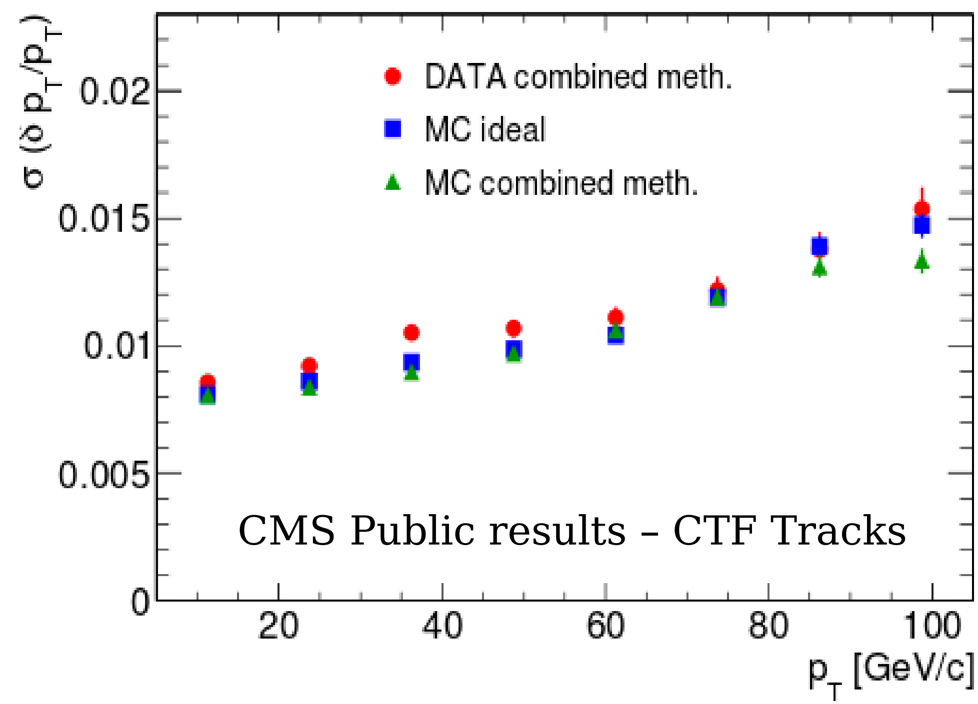
Tracking performance

CMS-TDR-011 : http://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf

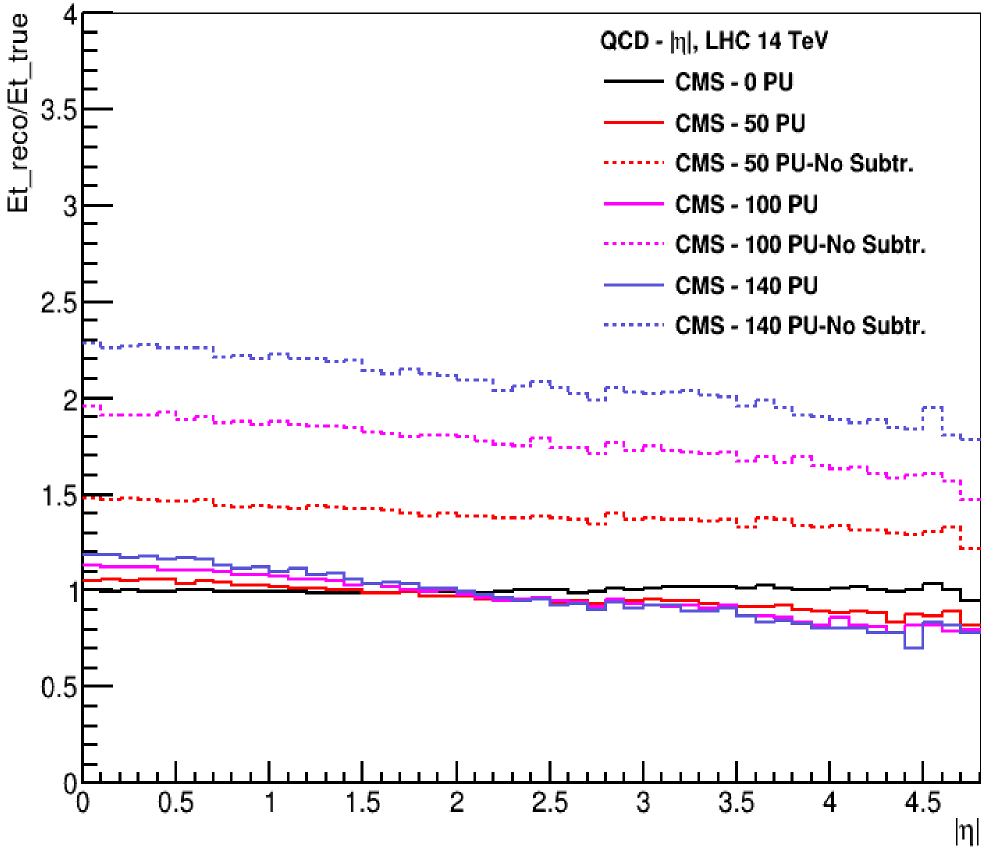


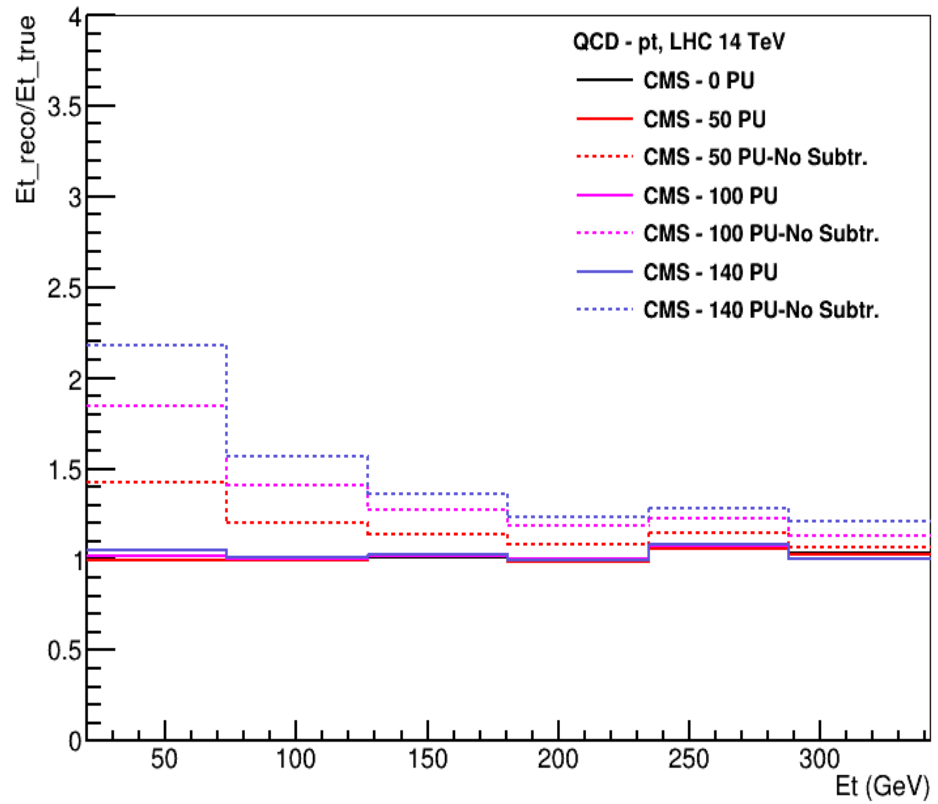






Detector response to (additional) jets





- Overall impact is still within 20% level with 140 PUs
- Plan to compare the performance with full simulation soon